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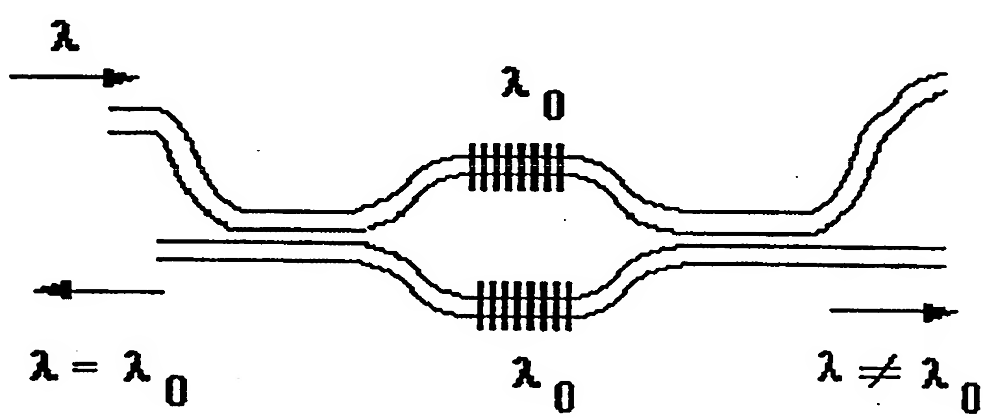

(57) Abstract

Disclosed is a wavelength-specific photonic device which utilizes sampled Bragg gratings positioned within arms of a waveguide Mach-Zehnder interferometer capable to add optical data signals to or separate optical data signals from multiple signals supplied to the photonic device by a fiber optic cable and to perform other wavelength-specific functions with signals. The wavelength-specific photonic device can resolve optical data signals having a channel spacing of less than 0.8 nm if desired, yet the device can be made to be specific for any wavelength in a communication bandwidth using photolithographic tools available in the electronics industry to fabricate the sampled Bragg gratings. The device is particularly useful in DWDM applications, where many signals with different wavelength within communication bandwidth are supplied through the same fiber optic cable. The device is particularly useful in the waveguides with intrinsic birefringence.

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WAVELENGTH-SPECIFIC PHOTONIC DEVICE FOR WAVELENGTH DIVISION MULTIPLEXED FIBER OPTIC NETWORKS BASED ON SAMPLED BRAGG GRATINGS IN WAVEGUIDE MACH-ZEHNDER INTERFEROMETER

This application claims priority to U.S. provisional application ser. no. 60/075,642, filed Feb. 23, 1998 and entitled "Wavelength-Specific Photonic Device For Wavelength Division Multiplexed Fiber Optic Networks Based On Sampled Bragg Gratings In Waveguide Mach-Zehnder Interferometer," inventor Valentine N. Morozov.

Field of the Invention

The invention pertains to wavelength-specific photonic devices for use in fiber optic telecommunications systems, particularly in wavelength-division multiplexing (WDM) systems including dense wavelength-division multiplexing (DWDM). This invention can be used to form devices, which handle multiple optical data signals such as a multiplexer/demultiplexer, an add/drop multiplexer , a cross-connect with multiple ports including wavelength specific cross-connect, and filters for fiber-dispersion cancellation.

Background

The increase in the number of telephones, fax machines, computers with modems, and other telecommunications service and equipment over the past several years has caused researchers to explore new ways to increase fiber network capacity through carrying multiple data signals concurrently through telecommunications lines. To expand fiber network capacity, WDM (wavelength division multiplexing) and DWDM (dense wavelength division multiplexing) technologies are in use. Fiber optics have provided a practical way to carry multiple optical data signals of differing wavelength simultaneously. Multiple optical data signals of different wavelength are added together in a device called multiplexer or combiner which can be realized through a number of

technologies, and the resulting mixed data signal is transmitted over a fiber optic cable. The transmitted optical data signals of different wavelength are separated from one another by e.g. a demultiplexer which also can be realized through a number of technologies.

Equipment designers are facing new challenges as they attempt to transmit more optical data signals simultaneously through a fiber optic cable to keep up with the demand for communication lines without having to install additional fiber optic cables and associated equipment. The lasers used to generate the different-wavelength optical data signals have a limited practical wavelength range in which the lasers can operate effectively and fiber optical amplifiers have limited amplification bandwidth. Consequently, as researchers seek to transmit more optical data signals of different wavelength simultaneously, the signals have become closer to one another in wavelength, and the permitted channel spacing within which each data signal is to be found has decreased.

A channel spacing of 100 GHz or 0.8 nm in vacuo between optical data channels is recommended by ITU (International Telecommunication Union) for DWDM fiber networks. Currently, costly production techniques must be used to make multiplexers and/or de-multiplexers capable of adding or separating optical data signals of such small wavelength spacing between channels.

For example, UV illumination through a phase mask was used to imprint Bragg gratings into two Ge-doped silica optical fibers. Forming Bragg gratings in fibers with a phase mask and UV illumination provides individual gratings with very good quality, but making fiber Bragg gratings is a slow and expensive process. Further, in order to provide systems that have practical use, a fiber Bragg grating should be connected to an optical circulator that limits optical signal propagation to one direction. Optical circulators are bulky optical devices and are comparatively expensive. Consequently, systems utilizing fiber Bragg gratings require a considerable amount of mounting space, and their cost prohibits their wide-spread use. in order to be able to use a fiber it is very difficult to assure that the arms of the interferometer are of equal length. It is usually necessary to

"trim" one arm of the interferometer by exposing one arm of the interferometer to ultraviolet ("UV") light to photoinduce an average index change in the fiber core, which adds processing cost and time into an already costly procedure. The fibers are delicate, they are bulky devices, and interfacing the fibers with e.g. cross-connects requires special design considerations.

Others have made wavelength-specific photonic devices by using planar Mach-Zehnder interferometers in well-known SiO_2/Si waveguide structures by recording Bragg gratings in photosensitive arms of the interferometers that have been sensitized by appropriate doping and exposing the waveguides to UV radiation pass through a phase mask having surface relief gratings. See, for example, U.S. Pat. No. 5,636,309, which describes a variant of this type of wavelength selective photonic device.

There is a need for a technology to make Bragg gratings in a waveguide Mach-Zehnder interferometer that is inexpensive and robust and yet produces a wavelength specific device that functions as a multiplexer-demultiplexer or similar device which resolves and handles multiple optical data signals having a channel wavelength spacing of only 0.8 nm or less. The invention provides a solution for the design and manufacture of such a device.

Summary of the Invention

The invention provides a wavelength-specific device that is useful in wavelength multiplexing and demultiplexing or other functions involving multiple optical data signals provided to the device, especially optical data signals in a DWDM communication system that can have as small of a channel spacing as about 0.8 nm or less. This device can be fabricated using optical lithographic tools currently utilized by modern electronics industry, avoiding the use of more expensive and less available technology such as e-beam lithography, X-ray lithography, phase-shift masks with UV illumination, and optical holography.

The wavelength-specific device of this invention has a first waveguide and a second waveguide positioned on a substrate so that the waveguides have a first optically-

coupled region, a second optically-coupled region, and an uncoupled region between the first and second optically-coupled regions where essentially no optical coupling occurs. The first optically-coupled region splits incoming lightwaves evenly between the first and second waveguides in the uncoupled region. The second optically-coupled region is identical to a first optically-coupled region. The first and second waveguides each contain a sampled Bragg grating having a sampling period sufficient to produce an optical reflection spectrum of peaks designed in such a way that one peak or more peaks correspond to one or more specific wavelengths amongst many contained in the multiple optical data signals within a communication bandwidth.

In one embodiment of the invention, the sampling period and/or length of the sampled Bragg grating is sufficient to reflect a first wavelength of the optical data signal, a second wavelength, a third wavelength, or more of desired wavelengths or all of them simultaneously. In another embodiment of the invention, the sampling period and/or length of the sampled Bragg grating is sufficient to provide a sufficiently large period of the reflection peaks that only one peak of the optical reflection spectrum is within a bandwidth suitable for data communication and the other peaks of the optical reflection spectrum are outside the bandwidth for data communication.

The invention also provides a method for making a wavelength-specific device useful in multiplexing and demultiplexing multiple optical signals. The method comprises (a) forming a first waveguide and a second waveguide on a substrate, such that the first waveguide and the second waveguide form a first coupled region, a second coupled region, and an uncoupled region, and (b) forming a first sampled Bragg grating in the first waveguide and an identical second sampled Bragg grating in the second waveguide in the uncoupled region. In one embodiment of the invention, each sampled Bragg grating has a sampling period and/or length sufficient to produce multiple optical spectrum sufficient to change the first wavelength, the second, the third or more or all of them simultaneously of the data signal. In another embodiment of the invention, the sampling period and/or length is sufficient to provide a sufficiently large period that a peak of the optical reflection spectrum is within a bandwidth suitable for data communication and the other peaks of the optical reflection spectrum are outside the

bandwidth for data communication. In another embodiment of the invention a few sampled gratings with different sampling periods positioned sequentially are formed in the first and in the second waveguide. Preferably, photolithography is used to fabricate the sampled Bragg grating of the interferometer.

The wavelength-specific device may also comprise a reflector made of sampled Bragg grating in one of the arms of the device. The reflector is positioned so that any optical signals that pass through the sampled Bragg grating in one arm of the device and through a coupled region positioned after the sampled Bragg grating are reflected. The invention also provides a device comprising two or more wavelength-specific devices as described above that is configured so that the output of one of the wavelength-specific devices is the input to the second wavelength-specific device. The device is useful for wavelength multiplexing or demultiplexing optical data signals from a fiber optic line, for example, and similar functions requiring selective action for a specific wavelength.

The device of this invention is useful in wavelength-division multiplexing (WDM) applications and particularly in dense wavelength-division multiplexing (DWDM) equipment. The device separates one optical data signal from the multiple data signals present in the data stream (or adds an optical data signal to other data signals in the data stream). The sampled Bragg grating of the device provides an optical reflection spectrum with multiple peaks, and the peaks are spaced about a central wavelength and have a specific period. The sampled Bragg grating can be designed so that this period is large enough that only one of the peaks is within a communication bandwidth and all other peaks of the optical reflection spectrum are outside the communication bandwidth. A pair of sampled Bragg grating can also be designed for use in a birefringent waveguide so that the first sampled Bragg grating has one or more peaks of the reflected optical signal within the communication bandwidth for the TE polarization mode and the second sampled Bragg grating has zero, one, or more peaks for the TM polarization mode of an optical signal within the communication bandwidth. Thus a pair of sampled Bragg gratings can be designed for use in a birefringent waveguide to produce peaks of the reflected signal within the communication bandwidth and which affect the TE and TM modes independently and simultaneously, thus compensating for birefringence inherent

in the waveguide. Specific relations for a sampling period and a refractive index birefringence should be satisfied as discussed herein to compensate for the different positions of the reflection peaks for TE and TM modes due to the birefringence.

A wavelength-specific device having a sampled Bragg grating can be fabricated using optical lithography (photolithography). The device can resolve optical signals having spectral channel spacing of only about 0.8 nm and/or less, despite the fact that the resolution of current photolithography is limited to features having a size slightly less than 250 nm. Typically, non-sampled Bragg gratings designed to separate two channels that are spaced about 0.8 nm apart should have a difference between their Bragg gratings periods of about 0.3 nm.

The wavelength-specific device having a sampled Bragg grating can also be designed to reflect a portion of the optical data signal and allow the remaining portion to pass through the interferometer along with the unreflected optical data signals. This feature permits the same data signal to be provided to a number of locations.

Among other factors, the invention is based on the technical finding that a wavelength-specific photonic device that has a sampled Bragg grating can be used in DWDM applications to separate, add, switch, or filter optical data signals. The device is easily fabricated using conventional photolithography, yet the device can separate optical data signals having a channel spacing of less than 0.8 nm. The device can also be designed so that polarization modes do not overlap when the device is made of materials that exhibit birefringence. These technical findings and advantages and others are apparent from the discussion herein.

Brief Description of the Figures

Fig. 1 illustrates a sampled Bragg grating.

Fig. 2 shows a reflection spectrum caused by a sampled Bragg grating for the following parameters: total sampled grating length $L = 2$ mm, $N_{eff} = 1.55$. $q = 2$ (second order Bragg grating), $\Lambda = 1$ μm, $Z_1 = 87.5$ μm, and $Z_0 = 200$ μm.

Fig. 3 shows a reflection spectrum caused by a sampled Bragg grating for the sampling period $Z_0 = 75$ μm and the same parameters L, N, q, and Z_1 above. The periodicity of the reflection spectrum depicted in Fig. 3 equals 10.33 nm.

Fig. 4 shows the spacing between the reflection peaks as a function of the sampling period. The parameters L, N, q, and Z_1 are the same as in Fig. 2 and Fig. 3. This figure illustrate tuning of the reflection peak to any desired position by changing a sampling period.

A Mach-Zehnder interferometer having a sampled Bragg grating is illustrated in Fig. 5.

Fig. 6 illustrates the optical spectra of reflected TE and TM modes where the birefringence ΔN is approximately equal to 0.01.

Fig. 7 illustrates the communication bandwidth and channel spacing for four multiplexed DWDM channels as an example.

Fig. 8 illustrates schematically two sampled Bragg gratings placed sequentially in a waveguide.

Fig. 9 illustrates the Bragg sampled grating reflectivity for the following parameters: total sampled grating length $L_g = 2$ mm, coupling coefficient $k = 30$ cm^{-1}, $N_{eff} = 1.55$, $Z_1 = 40$ μm, and $Z_0 = 28$ μm.

In Fig. 10 the spectrum of Fig. 9 is shown in a logarithmic scale.

Fig. 11 illustrates that two sampled Bragg gratings of different sampled Bragg period designed for TE and TM mode reflection may be placed at the top and/or bottom interfaces of the core and cladding.

Fig. 12 illustrates the spectral response of a sampled Bragg grating composed of 5 sections with coupling coefficients $k_1 = 10$ cm^{-1}, $K_2 = 30$ cm^{-1}, $K_3 = 60$ cm^{-1}, $K_4 = 30$ cm^{-1}, $K_5 = 10$ cm^{-1}.

A Mach-Zehnder waveguide interferometer with sampled Bragg gratings in it arms is illustrated in Fig. 13. In this embodiment, only one wavelength λ_0 of a data stream containing multiple wavelengths will be reflected in this structure, and the remaining wavelengths of the data stream pass through this structure.

A "consecutive" 1:4 demultiplexer is illustrated in Fig. 14.

Fig. 15 and Fig. 16 illustrate parallel demultiplexers formed using a wavelength-specific photonic device of this invention.

Fig. 17 illustrates a portion of compression molding equipment about to press upon a polymer film.

Fig. 18 illustrates how the compression molding equipment can form features such as small trenches suitable to form a sampled Bragg grating in a polymer film containing the waveguides. The small trenches can be subsequently filled by, e.g., pouring or spinning a layer of polymer onto the film to fill the trenches and optionally to form a layer of cladding as well.

Detailed Description of the Preferred Embodiment of the Invention

As discussed above, the invention provides a wavelength-specific photonic device that is useful in multiplexing and demultiplexing multiple optical data signals provided to the device, especially optical data signals used in DWDM communication systems and similar devices requiring wavelength specific operation on a multiple wavelength data stream provided to the device. The device has a first waveguide and a second waveguide positioned on a substrate so that the waveguides have a first optically-coupled region, a second optically-coupled region, and an uncoupled region between the first and second optically-coupled region where essentially no optical coupling occurs. The first optically-coupled region splits incoming lightwaves evenly into two light streams carried by a first and a second waveguide. The second optically-coupled region recombines the light streams of the optical data signal and is identical to the first optically-coupled region. The first and second waveguides each contain a sampled Bragg grating having a

sampling period sufficient to produce an optical reflection spectrum of reflection peaks positioned inside a communication bandwidth.

In one embodiment of the invention, the sampling period of the sampled Bragg grating is sufficient to reflect the first wavelength of the data signal; the second, the third and so on independently and/or simultaneously. In another embodiment of the invention, the sampling period is sufficient to provide a sufficiently large period so that only one peak of the optical reflection spectrum is within a bandwidth suitable for data communication and the other peaks of the optical reflection spectrum are outside the bandwidth for data communication.

DWDM communication systems have channel spacing as small as 100 GHz, or 0.8 nm and/or less. An interferometer such as a Mach-Zehnder interferometer having conventional, non-sampled Bragg gratings in its arms must be fabricated precisely in order to distinguish optical data signals which vary from one another by only 0.8 nm. The accuracy with which Bragg gratings must be fabricated in order to separate two optical data signals can be calculated as follows. The Bragg period Λ for a Bragg grating in a waveguide is given by the following equation:

$$\Lambda = \frac{\lambda}{2 N_{eff}}$$

where λ is the wavelength of the optical data signal to be reflected by the Bragg grating and N_{eff} is the effective refractive index of the waveguides. The Bragg period is 476.63 nm for a Bragg grating in which the effective refractive index of the waveguide $N_{eff} = 1.6260$ and the first optical data signal has λ=1550 nm. The Bragg period is 476.87 nm for the neighboring waveguide having the same N_{eff} but reflecting a second optical data signal having λ=1550.8 nm. The difference in the periods of the Bragg gratings is only about 0.24 nm. Clearly, it is a challenging issue for any technology to record multiple gratings with such similar periods and maintain these gratings independent of environmental changes. Fabrication of conventional Bragg gratings has usually been

realized by the use of e-beam lithography, holographic lithography, and phase masks technology.

Photolithography cannot provide a resolution sufficient to record conventional Bragg grating spectral filters designed for DWDM application. Photolithography is limited to a resolution of about the wavelength of the light being used to record features (approximately 250 nm or 1/4 micron). Consequently, it has not been possible to use photolithography to fabricate Bragg gratings with as a small difference as 0.24 nm in grating period.

The device of this invention can be fabricated using photolithography, yet the device can distinguish between optical data signals that have a channel spacing of 0.8 nm or less. For example, identical sampled Bragg gratings are fabricated in two arms of a Mach-Zehnder interferometer. Each sampled Bragg grating reflects an optical data signal having a particular wavelength and also produces an optical reflection spectrum having peaks whose period depends on the sampling period. The sampling period of the sampled Bragg grating is selected so that the period is large enough that only one peak of the reflection spectrum is within a communication bandwidth that contains all of the optical data signals, and all other peaks of the reflection spectrum are outside the communication bandwidth. Or, the sampling period of the sampled Bragg grating is selected to shift the wavelength of the optical data signal to another desired wavelength. One of the other peaks of the optical reflection spectrum can be used as the new optical data signal, or the optical reflection spectrum of the reflected optical data signal can have peaks that all have a wavelength different from the wavelength of the unreflected optical data signal. The sampling period of the sampled Bragg period may also be selected to both shift the wavelength of the optical data signal and to provide a period large enough that only one peak of the optical reflection spectrum is within the communication bandwidth. The communication bandwidth can be preselected, or the bandwidth can result from the particular selection of Bragg gratings present in a device in which the interferometer containing the sampled Bragg grating is incorporated. In one embodiment of the invention, the communication bandwidth is about 20 nm (1540-1560 nm), although larger communication bandwidths can be provided if desired.

A sampled Bragg grating is a conventional Bragg grating with grating elements removed in a periodic fashion. This leads to a periodic modulation of the reflectivity spectra. The position of the maxima or peaks in the spectrum is a function of the sampling period and is controlled by changing the sampling period.

Fig. 1 illustrates a sampled Bragg grating. It consists of equally spaced bursts of Bragg gratings with a period Λ. A length of a burst is Z_1 and period of a burst is Z_0. The sampled grating is a conventional grating multiplied by a sampled function.

The Fourier spectrum of a grating without sampling is:

$$F(\nu) = \delta(\nu - \nu_0)$$

where

$$\nu_0 = \frac{2\pi}{\Lambda}$$

is the Bragg grating spatial frequency. The Fourier spectrum of the sampled grating is:

$$F(\nu_n - \nu_0) = \frac{Z_1}{Z_0} \frac{\sin \pi n Z_1 / Z_0}{\pi n Z_1 / Z_0} \exp\left[i \pi n \frac{Z_1}{Z_0}\right]$$

where

$$\nu_n = n \frac{2\pi}{Z_0}$$

and n is the grating diffraction order, n= 0, ± 1, ± 2, ± 3, and so forth. Thus, the sampled grating is a sum of unsampled Bragg gratings with spatial frequencies

$$\gamma_n = \frac{2\pi}{\Lambda} + n\frac{2\pi}{Z_0}$$

The relationship between sampled Bragg grating and unsampled Bragg grating Fourier components translates into a relationship between the grating and sampled grating coupling coefficient:

$$k(n) = k_0 \frac{Z_1}{Z_0} \frac{\sin \pi n Z_1 / Z_0}{\pi n Z_1 / Z_0} \exp\left[i \pi n \frac{Z_1}{Z_0}\right]$$

If the spacing of the diffraction orders is larger than the order width, only one diffracted order will be phase matched at any wavelength and an analytic expression for the sampled grating reflectivity can be obtained by adapting the well known equation for the grating reflectivity:

$$r(\lambda) = \sum_n \frac{i k^*(n) \sin[q(n) L]}{q(n) \cos[q(n) L] - i \Delta\beta(n) \sin[q(n) L]} \quad (1)$$

where

$$\Delta\beta(n) = \frac{2\pi N_{eff}}{\lambda} - \frac{q\pi}{\Lambda} - \frac{\pi n}{Z_0} \qquad (2)$$

is detuning from the grating diffraction order n, N_{eff} is the effective refractive index at the wavelength λ, L is the length of the sampled grating, q is the Bragg diffraction order, and

$$[q(n)]^2 = [\Delta\beta(n)]^2 - |k(n)|^2$$

Expression (1) is an excellent approximation for sampled grating reflectivity if only one diffracted order is phase matched at any wavelength.

In Fig. 2, a reflection spectrum caused by a sampled Bragg grating is shown for the following parameters: total sampled grating length L = 2 mm, N_{eff} = 1.55, q = 2, Λ = 1 µm, Z_1 = 87.5 µm, and Z_0= 200 µm. Reflection of the sampled Bragg grating of the second order (q = 2,) was evaluated in this numerical example. It is seen from Fig. 2 that a reflection spectrum consists of a few peaks corresponding to different diffraction orders n. It follows from (1) that the peak power reflectivity of order n is:

$$R_{max}(n) = \tanh^2[k(n)L]$$

For n =0, the overall peak reflectivity is

$$R_{max}(0) = \tanh^2\left(k_0 \frac{Z_1}{Z_0} L\right) = \tanh^2(k_0 L_g)$$

where L_g is the total length of the grating. The spacing between reflectivity peaks

$$\Delta\lambda = \frac{\lambda^2}{2 Z_0 N_{eff}} \qquad (3)$$

is a function of the sampling period Z_0. Thus, the period of the peaks of the optical reflection spectrum is equal to $\Delta\lambda$ in equation (3) above. In Fig. 3 a reflection spectrum of the sampled Bragg grating is plotted for the sampling period $Z_0 = 75$ µm and the same parameters L, N, q, and Z_1. The period of the reflection spectrum depicted in Fig. 3 equals 10.33 nm.

The reflection spectrum periodicity can be controlled by the sampling period. As equation (3) shows, the period is increased by reducing the sampling period Z_0, or the period is decreased by increasing the sampling period Z_0 for a given wavelength and effective refractive index. Fig. 4 shows the spacing between the reflection peaks as a function of the sampling period. The parameters L, N, q, and Z_1 are the same as in Fig. 2 and Fig. 3. It is readily seen from Fig. 4 that changing the sampling period from 20 µm to 40 µm shifts the reflection peak periodicity up to 20 nm. This data also shows that the illustrated sampled Bragg reflector has a free spectral range (FSR) of about 20 nm and can cover the 15 nm bandwidth in vacuo required for DWDM systems.

The sensitivity of the reflectivity peak position to a sampling period change can be calculated from (3):

$$\delta(\Delta\lambda) = -\frac{\delta L}{L}\Delta\lambda$$

For L = 25 μm, a variation of the sampling period of 0.25 μm (the accuracy of current photolithography equipment) results in a reflectivity peak shift of about 0.2 nm. Thus, very fine control of the reflectivity peak position of a sampled Bragg grating is possible by relatively rough means, i.e., optical lithography with a resolution of approximately 0.25μm can be employed to control a position of the Bragg grating peak reflectivity with an accuracy of about 0.2 nm.

The photolithographic mask used to form the sampled Bragg grating of the first order can be designed with 0.5 μm pitch and equal line width and spacing within the pitch (0.25 μm). The photolithographic mask used to form the sampled Bragg grating of second order can be designed with 1 μm pitch and equal line width and spacing within the pitch (0.5 μm). The mask pattern can be drawn at 0.01 μm grid size and consequently the mask can be manufactured with 0.02 μm pitch increment. Two examples of pitch increments are presented below:

pitch increment 0.02 μm	pitch increment 0.04 μm
0.48-0.48 μm	0.46-0.46 μm
0.49-0.49 μm	0.48-0.48 μm
0.50-0.50 μm	0.50-0.50 μm
0.51-0.51 μm	0.52-0.52 μm
0.52-0.52 μm	0.54-0.54 μm

It is expected that the wavelength at which the sampled Bragg grating reflects an optical data signal can be selected within an accuracy of about 0.2 nm or even less. The particular wavelength can be further fine tuned using heat and/or laser annealing to slightly modify the material of the waveguides or cladding by methods well-known in the art.

One example of a Mach-Zehnder interferometer having a sampled Bragg grating is illustrated in Fig. 5. The interferometer is on a silicon substrate and is separated from the substrate by an oxide layer. The cladding layers are made of optical-quality polymer, and each core is made of optical-quality polymer having a higher refractive index than the cladding. Typical examples of polymers used to form the cores include Amoco's Ultradel 4212 and Hitachi's PIQ L100, OPI 1305, and OPI 2005. Cladding materials and materials used to form the sampled Bragg grating are materials such as polyimide, polyacrylate (such as polymethylmethacrylate), benzyl-cyclobutene, or polyquinoline. The materials used to produce cores, cladding, and/or sampled Bragg grating elements can be selected from a wide range of materials, including organic materials, inorganic materials and hybrid organic/inorganic materials, such as sol-gel glasses in a polymeric matrix. Sampled Bragg grating technology in Mach-Zehnder interferometers as described herein is also applicable to other waveguide material systems such as SiO_2/Si. The refractive indices of the cores, cladding, and sampled Bragg grating elements are selected to provide the desired transmission and reflection of optical data signals by methods well-known in the art.

The wavelength-specific photonic device can be designed to reflect essentially all of the power of the particular optical data signal that the sampled Bragg grating is designed to reflect to a data output. However, it can be useful to reflect only a portion of the particular optical data signal to the data output and allow the remainder of the optical data signal to pass through the wavelength-specific device along with the other optical data signals of different wavelengths that were unaffected by the sampled Bragg grating. The portion of the optical data signal passed through the device can be detected by other equipment downstream of the device, such as another multiplexer/demultiplexer, an add/drop device, or a cross-connect with multi-wavelength ports in which another wavelength-specific device of this invention is incorporated. The desired reflectivity of the sampled Bragg grating is supplied by, for example, selecting the refractive indices of the core, cladding, and sampled Bragg grating elements to provide a value of N_{eff} which causes only the desired amount of reflection of the optical data signal to the data output, as given by equation (1) above. The desired reflectivity may also be supplied by

selecting the length of the sampled grating, its sampling period, and/or its Bragg period, as given by equation (1) above.

Polarization-Independent Reflector Based on Sampled Bragg Gratings

Ideally, a genuine polarization-independent reflector should have identical reflection spectra, e.g. the same central wavelength and the same peak shapes, sizes, and periods for both TE and TM polarization. However, many materials exhibit birefringence, and it is often necessary to accommodate optical spectra which differ between the TE and TM modes. The phase matching condition is written for each polarization independently:

$$\Delta\beta^{TM}(n) = \frac{2\pi N^{TM}_{eff}}{\lambda} - \frac{q\pi}{\Lambda} - \frac{\pi n}{Z_0}$$

$$\Delta\beta^{TE}(n) = \frac{2\pi N^{TE}_{eff}}{\lambda} - \frac{q\pi}{\Lambda} - \frac{\pi n}{Z_0}$$

If ΔN (equal to $N^{TE}_{eff} - N^{TM}_{eff}$) is approximately 0.01, the difference in the reflection peak positions for TE and TM modes is approximately 10 nm at λ=1550 nm. Thus, one Bragg grating (with a fixed spatial period) exhibits two reflection peaks of the same order n, and the separation between the reflection peaks of the TE mode and the TM mode depends on the waveguide birefringence. Fig. 6 illustrates the optical spectra of the TE and TM modes where the birefringence ΔN is approximately equal to 0.01.

Fig. 6 illustrates the extent to which the reflectivity spectra of the TE mode is shifted compared to the TM mode, and it is quite possible that channel interference within the communication bandwidth of the DWDM system may occur. Fig. 7 illustrates the communication bandwidth and channel spacing for four multiplexed DWDM

channels, as an example. The channel spacing of $\delta\lambda_0$, equal approximately to 3.2 nm, and the communication bandwidth both satisfy ITU requirements. The total bandwidth of this four-channel WDM system is 12.8 nm.

The peaks of the TE and TM modes illustrated in Fig. 6 are separated by about 10 nm. To avoid the modes from interfering with other signals within a communication bandwidth of greater than 10 nm such as the one illustrated in Fig. 7, one of the peaks (for TE or for TM mode) can be shifted so that it is outside of the DWDM bandwidth. To do this, the waveguide birefringence should satisfy the following equation:

$$\Delta N > \Delta\lambda_B \frac{N_{eff}}{\lambda_0} \qquad (4)$$

where ΔN is the difference is between TE and TM refractive indices (i.e. $N^{TE}_{eff} - N^{TM}_{eff}$), $\Delta\lambda_B$ is the communications (e.g. DWDM) bandwidth, λ_0 is the central wavelength of the optical reflection spectrum, and N_{eff} is the mean effective refractive index. Assuming $\Delta\lambda_B = 12.8$ nm, $\lambda_0 = 1554$ nm, and $N_{eff} = 1.55$, birefringence should satisfy the following condition to avoid channel cross-talk:

$$N^{TE}_{eff} - N^{TM}_{eff} \geq 0.0128 \qquad (5)$$

One way to compensate for birefringence and satisfy equation (5) for the above-specified circumstances is to place a second sampled Bragg grating designed to reflect the TM mode after the first sampled Bragg grating, which is designed to reflect the TE mode. The TM mode passes through the first grating and is reflected from the second grating. The second grating is designed to shift the spectra of the TM mode so that none of its peaks are within the communication bandwidth.

The second sampled Bragg grating can have its sampling period selected to shift the wavelength of the TE or TM polarization mode an appropriate amount. Equations (3) and (4) above lead to the following relationship between the difference between the TE and TM refractive indices and the sampling period Z_0:

$$\frac{\lambda_0}{2 Z_0} < \Delta N \qquad (6)$$

where λ_0 is the wavelength of the mode whose wavelength is to be shifted.

The sampling period Z_0 of the second sampled Bragg grating is selected to be sufficiently large that equation (6) is satisfied for the materials used to make the interferometer. Note that, instead of or in addition to the sampling period being selected to shift the wavelength an appropriate amount, the second sampled Bragg grating can have its sampling period selected so that the optical period is larger than the communication bandwidth, as described previously.

Fig. 8 illustrates schematically two sampled Bragg gratings placed sequentially in a waveguide. The Bragg condition for the TE mode is fulfilled at the first sampled Bragg grating, and the Bragg condition is satisfied for the TM mode at the second sampled Bragg grating. Fig. 9 illustrates the Bragg sampled grating reflectivity for the following parameters: total sampled grating length L_g= 2 mm, coupling coefficient $k = 30\ cm^{-1}$, $N_{eff} = 1.55$, $Z_1 = 40\ \mu m$, and $Z_0 = 28\ \mu m$. The full width of the reflection coefficient at half of the maximum value of the reflection coefficient (FWHM) is about 0.5 nm. In Fig. 10 the same spectrum is shown in logarithmic scale.

Two (or more) sampled Bragg gratings may be placed in the arms of a Mach-Zehnder interferometer as illustrated in Fig. 8 to reflect two (or more) optical data signals

of different wavelength. Each sampled Bragg grating is designed to individually reflect one of the wavelengths of light of the optical data signals to be reflected as described previously, thus allowing the other wavelengths to pass through the grating unreflected. Thus, for example the sampling period and/or length of the first grating are selected to reflect one wavelength, and the sampling period and/or length of the second grating are selected to reflect a second wavelength.

Instead of placing the two sampled Bragg gratings sequentially as illustrated in Fig. 8, the two sampled Bragg gratings may be placed at the top and bottom interfaces of the core and cladding as illustrated in Fig. 11. The other arm of the interferometer will also have an identical set of these gratings placed at the top and bottom interfaces of the core. Also, instead of placing the two sampled Bragg gratings sequentially, the sampling period across a single grating may be changed so that the single grating is, in effect, two separate sampled Bragg gratings that are combined into one.

Sampled Bragg Grating Spectral Response Apodization

The sampled Bragg grating may be apodized to reduce sidelobes by "chirping" the grating. The spectral response of a uniform Bragg grating varies approximately as a sinc squared function. This produces an optical reflection spectrum with "sidelobes" or peaks of large amplitude that can overlap with other optical data signals and cause cross-talk.

Apodizing the coupling strength of a waveguide grating and refractive index chirping along the propagation direction of the optical data signal results in a reflection spectrum with significantly reduced sidelobes and flattened spectral response. A chirped grating has a period Λ that changes gradually across the grating. Thus, instead of having a uniform period Λ of, e.g., about 0.5 μm, the grating period Λ changes for adjacent elements. For example, the first two elements may be spaced a distance of 0.5 μm from one another, the second and third elements may be spaced 0.55 μm from one another, the third and fourth elements may be spaced 0.5 μm from one another, the fourth and fifth elements may be spaced 0.55 μm from one another, and so forth to the last element. In

these apodized gratings, sidelobes can be strongly suppressed, and the optical reflection spectrum of the reflected data signal begins to approach an ideal, rectangular-shaped response. Providing grating grooves which have depths that gradually decrease in the direction that the optical data signal travels before it first contacts the sampled Bragg grating can also effect apodization. The effective refractive index N_{eff} of the grating thus varies across the length of the grating.

Spectral characteristics of an amplitude-modulated, linearly chirped Bragg planar waveguide grating can be calculated. A nearly ideal filter based on linearly chirped sampled Bragg gratings can been designed, and its performance can be calculated using the transfer matrix method. This method approximates the non-uniform grating by dividing the grating into a number of sections, where each section is described analytically and for every section a 2x2 transfer matrix is generated. A transfer matrix obtained by multiplying all the matrices of the individual sections then describes the action of the entire grating. The number of sections is selected to be large enough for high quality approximation. Fig. 12 illustrates the spectral response of a sampled Bragg grating composed of 5 sections with coupling coefficients $k_1 = 10\ cm^{-1}$, $K_2 = 30\ cm^{-1}$, $K_3 = 60\ cm^{-1}$, $K_4 = 30\ cm^{-1}$, $K_5 = 10\ cm^{-1}$. Thus, discrete coupling coefficients distributed among 5 sections are used to simulate the continuous Gaussian distribution of the coupling coefficient along a waveguide. The oscillation of the spectral response due to the coupling coefficient being calculated as discrete values is clearly seen in Figure 12. Better apodization results are achieved by increasing the number of sections.

Figure 12 illustrates that coupling coefficient amplitude modulation is an effective means for channel isolation and, when combined with grating chirp, can theoretically result in approximately –40 dB channel isolation.

Other Devices that Incorporate the Interferometer

A wavelength-selective multiplexer/demultiplexer can be built around a wavelength-specific photonic device of this invention. A wavelength selective filter is illustrated in Fig. 13.

This filter has a sampled Bragg grating in the arms of the Mach-Zehnder interferometer. If the wavelength of the input optical data signal is outside the stopband of the grating, the demultiplexer acts as a simple directional coupler, and the optical data signal transfers to the transmitted port of the coupler. If the wavelength of the input signal is within the stopband of the grating, the signal propagates half the coupling length and is reflected back by the grating. Propagating half the coupling length again, the signal light transfers to the reflected port of a Mach-Zehnder interferometer.

Many versions of a demultiplexer can be fabricated using a Mach-Zehnder interferometer (MZI) with sampled Bragg gratings of this invention. A "consecutive" 1:4 demultiplexer is illustrated in Fig. 14 as an example. This demultiplexer has a number of MZIs formed from photonic devices of this invention, the number of photonic devices being equal to the number of optical data signals to be separated by the demultiplexer. Each of the gratings illustrated in this demultiplexer is a sampled Bragg grating, although it is not necessary for all of the gratings to be sampled gratings. In this consecutive demultiplexer, four MZIs are placed consecutively one behind the other, and a lightwave can propagate along the entire chain. When an optical data signal has a wavelength that coincides with the sampled Bragg grating stopband, the signal is reflected (demultiplexed) to the specific output port of the demultiplexer. Any or all of the MZIs illustrated could also be a polarization-independent reflector and may be apodized or non-apodized, as described previously.

The number of MZIs required to separate optical data signals can be fewer than the number of optical data signals, as illustrated by the parallel demultiplexers of Fig. 15 and Fig. 16. In these demultiplexers, two or more gratings are embedded in an arm of at least one of the Mach-Zehnder interferometers. The stopbands of these gratings are different, and the number of optical data signals reflected to the output port is equal to the number of gratings in the arms of the interferometer. In a parallel demultiplexer, the minimum number of interferometers needed to demultiplex N channel is Log_2N, and the number of directional couplers is reduced by approximately N/ Log_2N times. A different form of parallel demultiplexer is presented in Fig. 16.

A combination of a consecutive demultiplexer and a parallel demultiplexer is also possible depending on the requirements to multiplex and demultiplex the optical data signals.

Method of Making

Generally, one method for making a device of this invention comprises (a) forming a first waveguide and a second waveguide on a substrate, such that the first waveguide and the second waveguide form a first coupled region, a second coupled region, and an uncoupled region, and (b) forming a first sampled Bragg grating in the first waveguide and an identical second sampled Bragg grating in the second waveguide in the uncoupled region. In one embodiment of the invention, each sampled Bragg grating has a sampling period sufficient to produce an optical reflection spectrum enabling to reflect an optical data signal having a first wavelength, the second wavelength, the third and so on, independently and/or simultaneously for entire communication bandwidth. In another embodiment of the invention, the sampled Bragg grating of the device has a sampling period that is sufficient to produce an optical reflection spectrum with a sufficiently large period that only one peak of the optical reflection spectrum is within a bandwidth suitable for data communication and the other peaks of the optical reflection spectrum are outside the bandwidth for data communication.

A Mach-Zehnder interferometer with sampled Bragg gratings and other devices of this invention can be made using conventional photolithography with a resolution/feature size equal to a half of the Bragg grating period Λ in a waveguide. As discussed above, an interferometer having an unsampled Bragg grating could not be made using conventional photolithography with sufficient precision that the interferometer could be used in DWDM communications, i.e. to be manufactured for different closely spaced wavelength. However, an interferometer produced using photolithographic equipment in use and available today can be used in DWDM applications when the device has a sampled Bragg grating and the sampling period of the sampled Bragg grating is selected

as described previously to tune a reflection peak to any specific wavelength in a communication bandwidth.

Existing photolithographic equipment uses a light source such as an arc lamp or an excimer laser, which produce UV light, and a mask through which the UV light passes in order to expose a layer of photoresist placed over an optical material on a substrate. The developed photoresist provides a pattern on the substrate, and areas that are unprotected by the photoresist are etched. The etched regions can be filled with other optical material such as an optical-quality polymer to form waveguide core or cladding regions or grating elements for the sampled Bragg grating.

For example, a first polymer layer is placed on a substrate by spinning a first polymer onto an oxide layer that covers the substrate and curing the polymer layer. The first polymer has a refractive index suitable to make the polymer the cladding of waveguides that are to be formed in and/or on the polymer layer. A photoresist is spun onto the first polymer layer and is exposed to UV light passing through a mask that defines waveguide channels through the cladding. The photoresist is developed, and the polymer that is unprotected by the developed photoresist is etched in a reactive-ion etcher. The photoresist is stripped, and a second layer of a second polymer is spun onto the first polymer, cured, and planarized so that only the channels contain the second polymer. The second polymer has a refractive index suitable for the filled channels to be cores of waveguides. A third layer is formed over the cores and the first layer by spinning a third polymer (typically, the third polymer is identical to the first polymer) onto the first layer and curing the polymer. The third layer has a refractive index suitable for cladding for the waveguides being formed on the substrate. Another layer of photoresist is spun onto the third polymer layer and is patterned by passing light through a mask that defines the lines or elements of the sampled Bragg grating. The photoresist is developed, and the third polymer layer is etched in a reactive-ion etcher to form channels that extend through the third layer and partially into the cores and the first layer. The photoresist is again stripped and a fourth polymer layer is spun onto the third layer to fill the channels. The fourth polymer has a refractive index suitable to make the grating elements of the sampled Bragg grating with selected strength that reflects an optical data

signal having a particular wavelength. The width of each element of the sampled Bragg grating is usually as small as possible and is consequently limited to a width of about somewhat less than 0.25 micron (the wavelength of the UV light used to pattern the photoresist). The period of the elements of a "burst" of the sampled Bragg grating Λ is equal to the period of the elements of the sampled Bragg grating (about 0.5 micron). The waveguide width and sampling period can vary along the length of the sampled Bragg grating to provide a chirped and apodized grating that will modify the optical reflection spectrum produced by the grating to meet ITU requirements for the cross-talk value and flatness of the reflection spectra. The depth of each channel used to form an element can be controlled by adjusting the amount of time that the channel is etched with reactive ions. The depth is selected based on the amount of reflectivity desired in the sampled Bragg grating, the refractive indices of the core, cladding, and Bragg element polymers, and the effective index desired for the sampled Bragg grating. An alternate way to supply a chirped and apodized grating is to modify the width of a waveguide, so that the waveguide becomes wider along the length of the waveguide through the portion of the waveguide in which the grating is located. The length of the sampled Bragg grating is also selected based on the desired reflectivity for the grating and also may be selected to provide the desired the reflection spectra width (a longer length giving a narrower reflection spectrum bandwidth and smaller channel spacing consequently).

Another example of a particular method for making an interferometer or other device of this invention is similar to the one just described. The first polymer layer and cores are formed as described above. After planarizing the second polymer to form cores, a photoresist is spun onto the cores and first layer, and light is passed through a mask that defines the elements of the sampled Bragg grating to expose the photoresist. The polymer unprotected by the photoresist is etched to form channels that extend partially into the depth of the cores and cladding. The channels are also perpendicular to the cores and extend across the width of the cores and partially into the cladding. The channels are filled with a third polymer having a refractive index suitable for elements of the sampled Bragg grating, and the third polymer layer is planarized so that only the channels are filled with the third polymer, and essentially none of the third polymer

remains over the core and cladding in areas other than the channels. Subsequently, a polymeric cladding layer is spun over the planarized surface to complete the interferometer.

It is not necessary to use photolithography to form the cores and grating elements. E-beam lithography, X-ray lithography, or phase-shift masks and holography can be used to define the grating elements and/or cores, if desired. However, photolithography is an attractive and practical alternative to these more exotic methods and could not otherwise be used to form grating elements of interferometers capable of resolving optical data signals of small channel spacing as are present in DWDM communications.

Another method of making a device of this invention is to utilize compression molding equipment and systems to form features in a polymer. Compression molding equipment usually has separate male and female mold portions that join to form a compression molding chamber of a desired shape. Typically, the male mold portion is placed on a hydraulic ram that is used to push the male mold portion into the female mold portion.

As illustrated in Fig. 17, a substrate 1710 carrying a polymer film 1720 is placed within the chamber beneath mold plunger 1730. The polymer film 1720 is heated to a temperature above its glass transition temperature by the pressure and compressive forces created by the male mold portion 1730 pushing the polymer against the female mold portion and/or by heating at least one of the male and female mold portions as illustrated in Fig. 18, allowing the polymer to reflow either locally or completely to form a molded object. Features such as trenches can thus be "stamped" into either a blank or a piece that has undergone some intermediate processing. Or. the entire polymer within the molding chamber can reflow and assume the shape of the molding chamber.

The polymer within the molding chamber is held for a suitable period of time to form the features by e.g. reflowing, melting, or curing the polymer, and the polymer is cooled within the chamber to allow the polymer to take the final shape of the molded object. The male and female portions separate to allow the molded object to be removed from the molding chamber and to recharge the chamber with polymer.

One method of making a device of this invention is to first form a Mach-Zehnder interferometer with no sampled Bragg grating using polymers having suitable refractive indices to form the cores and cladding of the interferometer. The polymeric Mach-Zehnder interferometer is placed within the compression chamber of the compression molding equipment so that an alignment notch, hole, and/or stud that is part of the Mach-Zehnder interferometer structure properly aligns the interferometer to the mold portions. The male and female mold portions are then joined together.

Fins formed on the male and/or female mold portions press against the cores and cladding, forming trenches in the cores and cladding. The fins have a length, width, height, and spacing from one another suitable to form indentations that, when filled with polymer, form the sampled Bragg grating. The molded interferometer can be removed from the compression molding equipment in order to spin-coat a layer of polymer having a refractive index suitable to form the sampled Bragg grating onto the indented surface of the interferometer and fill the trenches. If desired, the layer can be etched to remove the layer to the indented surface of the interferometer, leaving the trenches filled with the polymer. A second polymer can be spun onto the surface to provide a cladding layer.

It is also possible to form core trenches or ribs using this technique. Polymer in the form of pellets, sheet, wafer, block, or a preformed shape that approximates the shape of the molded object is placed within the compression molding chamber. The male and/or female mold portions are shaped to provide trenches within the molded object and/or are shaped to provide ribs on the surface of the molded object.

To form trenches, essentially the total mass of polymer that is placed within the compression molding chamber is melted by providing sufficient pressure and/or heat to melt the polymer so that it assumes the shape of the compression molding chamber.

To form core ribs on one side of a cladding, a wafer or sheet of polymeric cladding is placed within the compression molding chamber, and polymer having a refractive index suitable to form cores is placed on the polymeric cladding. The mold portion that contacts the polymer used to form cores has trenches cut within it, so that ribs are formed on the polymeric cladding when the male and female portions are joined.

In either case, the polymer is held at temperature for a sufficient period of time to allow the polymer to assume the shape of the chamber and optionally to cure. The polymer is cooled, and the molded object is removed.

Cores can be formed by spin-coating polymer of suitable refractive onto the surface of the molded object having the trenches, thus forming a layer and filling the trenches. The layer can be etched or polished to remove the polymeric layer to the surface of the molded object, leaving the trenches filled with core material and thus forming an intermediate structure. Another layer of polymer having a refractive index suitable to form a cladding may be spun-coated onto the intermediate structure to form a waveguide structure such as a Mach-Zehnder interferometer.

If core ribs were formed in the compression molding chamber, a polymer having a suitable refractive index to form cladding may be spun-coated onto the molded object to produce a waveguide structure such as a Mach-Zehnder interferometer.

The polymer preferably is one that easily releases from the male and female mold portions. The polymer also preferably exhibits predictable or little shrinkage or expansion during cool-down or after being released from the mold portions, so that the dimensions of the features formed using the compression molding equipment are the desired dimensions.

A compression molding system as used in forming medical devices could be used to produce such waveguide structures as cores and sampled Bragg gratings. A compression molding system has compression molding equipment and, for example, polymer handling equipment to charge the compression molding chamber, a molded object extraction system to remove the molded object from the compression molding chamber, an enclosure and clean air system that surrounds the compression molding equipment to provide a clean-room environment and prevent foreign particles from being incorporated in the core, cladding, and/or grating elements.

The male and/or female mold portions can have ridges and/or trenches formed on their surfaces that contact the polymer within the compression molding chamber. One of

the male and/or female mold portions may have a smooth surface so that one face of the molded object is smooth, or both mold portions may have ridges and/or trenches so that the molded object has complementary trenches and/or ridges, respectively, on two or more faces of the molded object. The mold portions can be formed of a suitable metal such as stainless steel or other alloys and may be coated with a non-stick coating such as a polytetrafluoroethylene polymer that is non-reactive with and non-depositing on the polymers used to form waveguide structures. The mold portions that contact the polymer may instead be formed of a dielectric such as SiO_2, diamond, or other material. A metal layer such as nickel can be deposited on the mold. The ridges and/or trenches on the mold portions can be formed by machining the material or by etching a pattern formed by e-beam lithography, for example, to form ridges and/or trenches of the correct size, shape, and spacing to form the desired features in the molded object.

The ridges and/or trenches may be rectangularly-shaped, but other shapes are possible. The ridges and/or trenches may be semi-cylinders that have been cut along the axis of the cylinder, for example, or may similarly be semi-ellipses that have been cut along a major or minor axis.

Compression molding may also be used to imprint a lithographic mask. Imprint lithography provides a minimum feature size of about 25 nm and period of about 7 nm in photoresist that is at least about 100 nm thick. A mold having ridges and/or trenches as described above is pressed into a thin photoresist layer that has been spun onto a polymer to be etched. The polymer may be a core material, a cladding material, or the product of an intermediate step in forming a waveguide structure (such as a Mach-Zehnder interferometer). The photoresist is preferably a polymer that can be patterned by the mold as described previously.

The photoresist can be etched using conventional etching techniques such as oxygen reactive-ion etching to remove the photoresist from the thinnest areas created by the mold. The underlying polymeric core, cladding, and or grating elements may then be etched through the photoresist using conventional techniques.

While certain preferred embodiments of the invention have been illustrated and discussed above, these preferred embodiments are not to be limiting on the scope of the claimed invention, and the claims are to be given their broadest reasonable scope that is consistent with the principles and discussion herein.

What is claimed is:

1. A device useful in multiplexing and demultiplexing multiple optical data signals provided to the device simultaneously, said multiple optical data signals having multiple wavelengths within a communication bandwidth for the multiple optical data signals, wherein the device comprises a first waveguide and a second waveguide positioned on a substrate to form a first optically-coupled region, a second optically-coupled region, and an uncoupled region disposed between the first and second optically-coupled regions, and wherein, in the uncoupled region, the first waveguide contains a first sampled Bragg grating having a sampling period and a length, the second waveguide contains a second sampled Bragg grating identical to the first sampled Bragg grating, and the first sampled Bragg grating is configured to produce an optical reflection spectrum having multiple reflection peaks of period p from an optical data signal of the multiple optical data signals.

2. The device of claim 1 wherein the first sampled Bragg grating is adapted to provide said period p with a sufficient magnitude that a peak of the optical reflection spectrum having a first wavelength is within the communication bandwidth and all other peaks of the multiple peaks are outside the communication bandwidth.

3. The device of claim 2 wherein the sampling period of the first sampled Bragg grating is selected such that the period p is sufficiently large that said peak of the optical reflection spectrum is within the communication bandwidth and all other peaks of the multiple peaks are outside the communication bandwidth.

4. The device of claim 2 wherein the sampling period and the length of the first sampled Bragg grating are selected such that the period p is sufficiently large that said peak of the optical reflection spectrum is within the communication bandwidth and all other peaks of the multiple peaks are outside the communication bandwidth.

5. The device of claim 2 wherein the device further comprises a reflector positioned in the first waveguide and located after the second optically-coupled region so

that the reflector reflects the multiple optical data signals that pass through the sampled Bragg grating of the first waveguide.

6. The device of claim 5 wherein the sampling period and the length of the first sampled Bragg grating are sufficient to provide a channel spacing for the multiple optical data signals of no more than about 3.2 nm.

7. The device of claim 6 wherein the sampling period and the length of the first sampled Bragg grating are sufficient to provide a channel spacing for the multiple optical data signals of no more than about 0.8 nm.

8. The device of claim 2 wherein the peak of the optical reflection spectrum within the communication bandwidth has a wavelength that is different from the first wavelength of the optical data signal.

9. The device of claim 1 wherein the first sampled Bragg grating is adapted to reflect a portion of the optical data signal to an output of the interferometer and to permit a portion of the optical data signal to pass through the first sampled Bragg grating.

10. The device of claim 9 wherein the length of the first sampled Bragg grating is sufficient to reflect said portion of the optical data signal and to permit said portion of the optical data signal to pass through the first sampled Bragg grating.

11. The device of claim 1 wherein the first sampled Bragg grating is configured such that none of the multiple peaks of the optical reflection spectrum is within the communication bandwidth.

12. The device of claim 1 wherein the device further comprises a third sampled Bragg grating in the first waveguide and a fourth sampled Bragg grating in the second waveguide, the third sampled Bragg grating is identical to the fourth sampled Bragg grating, the first waveguide has a first core comprised of a birefringent material that generates a first polarization mode and a second polarization mode from the optical data signal, the second waveguide has a second core comprised of the birefringent material. the first sampled Bragg grating is configured to generate said optical reflection spectrum

from the first polarization mode of the optical data signal such that none of the multiple peaks of the optical reflection spectrum produced by the first sampled Bragg grating is within the communication bandwidth, and wherein the third sampled Bragg grating is configured to provide a second optical reflection spectrum of period p_1 from the second polarization mode of the optical data signal such that one of the multiple peaks of the optical reflection spectrum is within the communication bandwidth and all remaining peaks of the optical reflection spectrum are outside the communication bandwidth.

13. The device of claim 12 wherein the first sampled Bragg grating and the third sampled Bragg grating are positioned in series in the first waveguide, and the second sampled Bragg grating and the fourth sampled Bragg grating are positioned in series in the second waveguide.

14. The device of claim 12 wherein the first sampled Bragg grating and the third sampled Bragg grating are positioned on opposite sides of the first core, and the second sampled Bragg grating and the fourth sampled Bragg grating are positioned on opposite sides of the second core.

15. The device of claim 11 wherein the sampling period of the first sampled Bragg grating is selected such that none of the multiple peaks of the optical reflection spectrum is within the communication bandwidth.

16. The device of claim 11 wherein the sampling period and the length of the first sampled Bragg grating are selected such that none of the multiple peaks of the optical reflection spectrum is within the communication bandwidth.

17. The device of claim 1 wherein the first waveguide comprises a first polymeric core and a polymeric cladding and the second waveguide comprises a second polymeric core and said polymeric cladding.

18. The device of claim 1 wherein the device further comprises a reflector positioned in the first waveguide and after the second optically-coupled region so that the reflector reflects the multiple optical data signals that pass through the sampled Bragg grating of the first waveguide.

19. The device of claim 18 wherein the sampling period and the length of the first sampled Bragg grating are sufficient to provide a channel spacing for the multiple optical data signals of no more than about 3.2 nm.

20. The device of claim 19 wherein the sampling period and the length of the first sampled Bragg grating are sufficient to provide a channel spacing for the multiple optical data signals of no more than about 0.8 nm.

21. The device of claim 1 further comprising a third waveguide and a fourth waveguide positioned on the substrate to form a third coupled region, a fourth coupled region, and a second uncoupled region disposed between the third and fourth coupled regions, wherein, in the second uncoupled region, the third waveguide contains a third sampled Bragg grating, the fourth waveguide contains a fourth sampled Bragg grating identical to the third sampled Bragg grating, the third waveguide being optically connected to an end of the second waveguide so as to receive the multiple optical data signals that pass through the second coupled region, wherein said optical data signal has a first wavelength, and wherein the third Bragg grating is configured to produce an optical reflection spectrum of period p_2 from a second optical data signal of the multiple optical data signals that pass through the second coupled region, said second optical data signal having a second wavelength which differs from the first wavelength.

22. The device of claim 2 further comprising a third waveguide and a fourth waveguide positioned on the substrate to form a third coupled region, a fourth coupled region, and a second uncoupled region disposed between the third and fourth coupled regions, wherein, in the second uncoupled region, the third waveguide contains a third sampled Bragg grating, the fourth waveguide contains a fourth sampled Bragg grating identical to the third sampled Bragg grating, the third waveguide being optically connected to an end of the second waveguide so as to receive the multiple optical data signals that pass through the second coupled region, wherein said optical data signal has a first wavelength, and wherein the third Bragg grating is configured to produce a second optical reflection spectrum of period p_2 from a second optical data signal of the multiple optical data signals that pass through the first and second sampled Bragg gratings, said

second optical data signal having a second wavelength which differs from the first wavelength, and wherein the third sampled Bragg grating is adapted to provide said period p_2 of sufficient magnitude that a peak of the second optical reflection spectrum is within the communication bandwidth and all other peaks of the multiple peaks are outside the communication bandwidth.

23. A method of making a device useful in multiplexing and demultiplexing multiple optical data signals within a communication bandwidth, wherein the method comprises

a) forming a first waveguide and a second waveguide on a substrate, such that the first waveguide and the second waveguide form a first coupled region, a second coupled region, and an uncoupled region, and

b) forming in the uncoupled region a first sampled Bragg grating in the first waveguide and a second sampled Bragg grating identical to the first sampled Bragg grating in the second waveguide, the first sampled Bragg grating having a sampling period sufficient to produce an optical reflection spectrum having multiple peaks with a period p from an optical data signal having a first wavelength.

24. The method of claim 23 wherein the first and second sampled Bragg gratings are formed by placing a polymeric layer over the first and second waveguides and compression molding the polymeric layer to form the first and second sampled Bragg gratings.

25. The method of claim 23 wherein said waveguides are formed by placing a first layer of a core polymer over a second layer of a cladding polymer and compression molding the first layer and the second layer to form said waveguides.

26. The method of claim 25 wherein the first and second sampled Bragg gratings are formed by placing a third polymeric layer over said waveguides and compression molding the polymeric layer to form the first and second sampled Bragg gratings.

27. The method of claim 23 wherein the first sampled Bragg grating and the second sampled Bragg grating are formed by placing a photoresist over a cladding layer that contains a first core and a second core, exposing the photoresist to light passing through a mask, developing the photoresist, etching the first core, second core, and cladding layer in areas that are unprotected by the photoresist to form element channels, and filling the element channels with a material having a refractive index that is suitable to reflect the optical data signal.

28. The method of claim 27 wherein the first core and the second core are formed by placing a photoresist over a polymeric cladding layer, exposing the photoresist to light passing through a mask, developing the photoresist, etching the polymeric cladding layer in areas that are unprotected by the photoresist to form core channels, and filling the core channels with a polymeric material having a refractive index that is suitable to carry the multiple optical data signals, thereby forming the cladding layer that contains the first core and the second core.

29. The method of claim 28 wherein the element channels are filled with a polymeric material.

30. The method of claim 23 wherein the first sampled Bragg grating is formed so that the sampling period and length of the first sampled grating are sufficient that a peak of the optical reflection spectrum is within the communication bandwidth and so that remaining peaks of the optical reflection spectrum are outside the communication bandwidth.

31. A device made by the method of claim 24.

32. A device made by the method of claim 25.

33. A device made by the method of claim 26.

34. A device made by the method of claim 27.

35. A device made by the method of claim 29.

36. A device made by the method of claim 30.

37. A method for preventing interference of data signals within a communication bandwidth transmitted through a birefringent material, said method comprising providing a device having a first waveguide and a second waveguide positioned on a substrate to form a first coupled region, a second coupled region, and an uncoupled region disposed between the first and second coupled regions, and forming in the uncoupled region a first sampled Bragg grating and a third sampled Bragg grating in the first waveguide and a second sampled Bragg grating and a fourth sampled Bragg grating in the second waveguide, the first and second sampled Bragg gratings being identical and being adapted to reflect a first polarization mode of the optical data signal to generate a first optical reflection spectrum such that a peak of the first optical reflection spectrum is within the communication bandwidth, and wherein the third and fourth sampled Bragg gratings are identical and are adapted to reflect a second polarization mode of the optical data signal to generate a second optical reflection spectrum having peaks such that the peaks of the second optical reflection spectrum are outside the communication bandwidth.

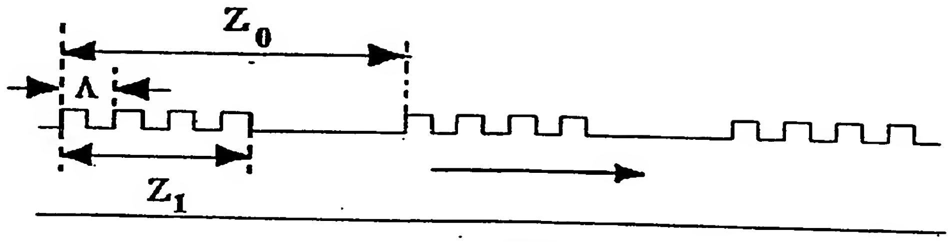

Fig. 1

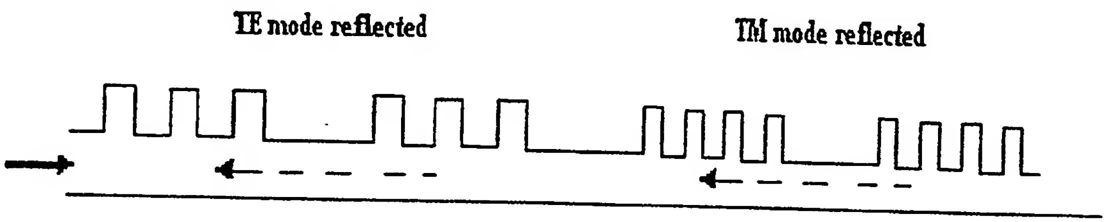

Fig. 8

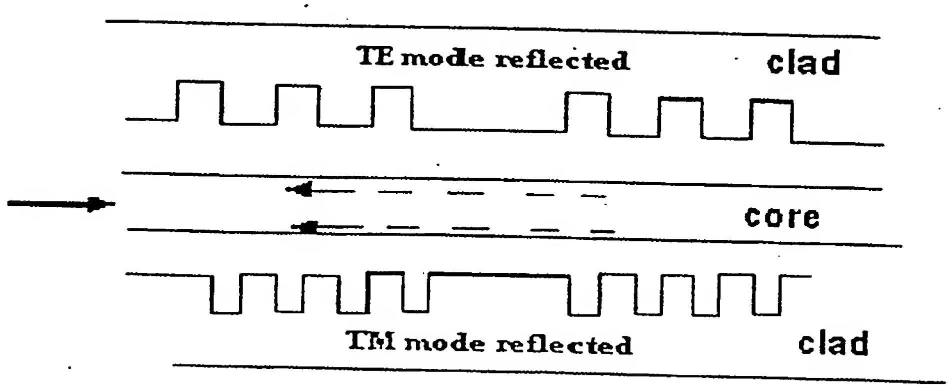

Fig. 11

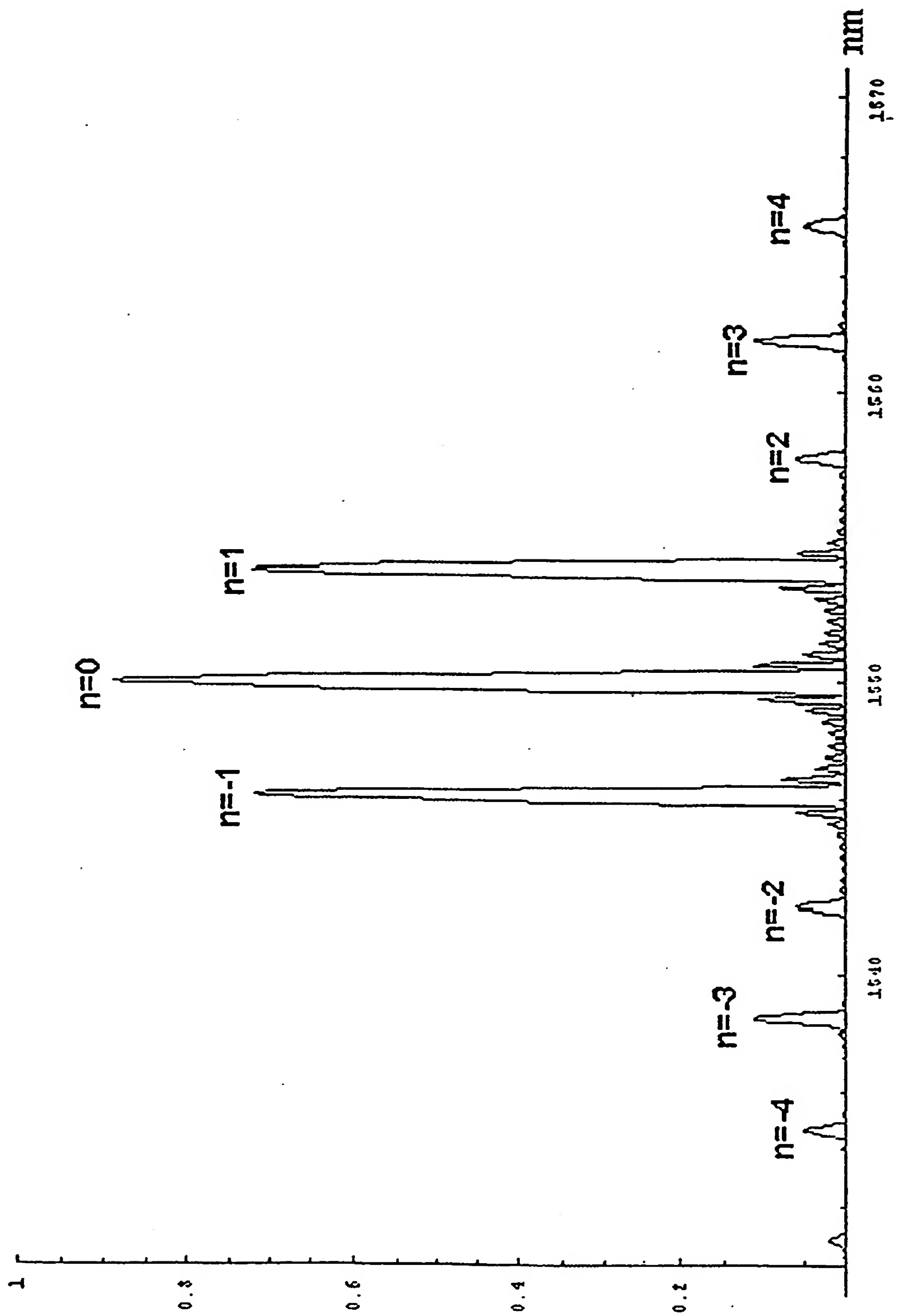

Fig. 2

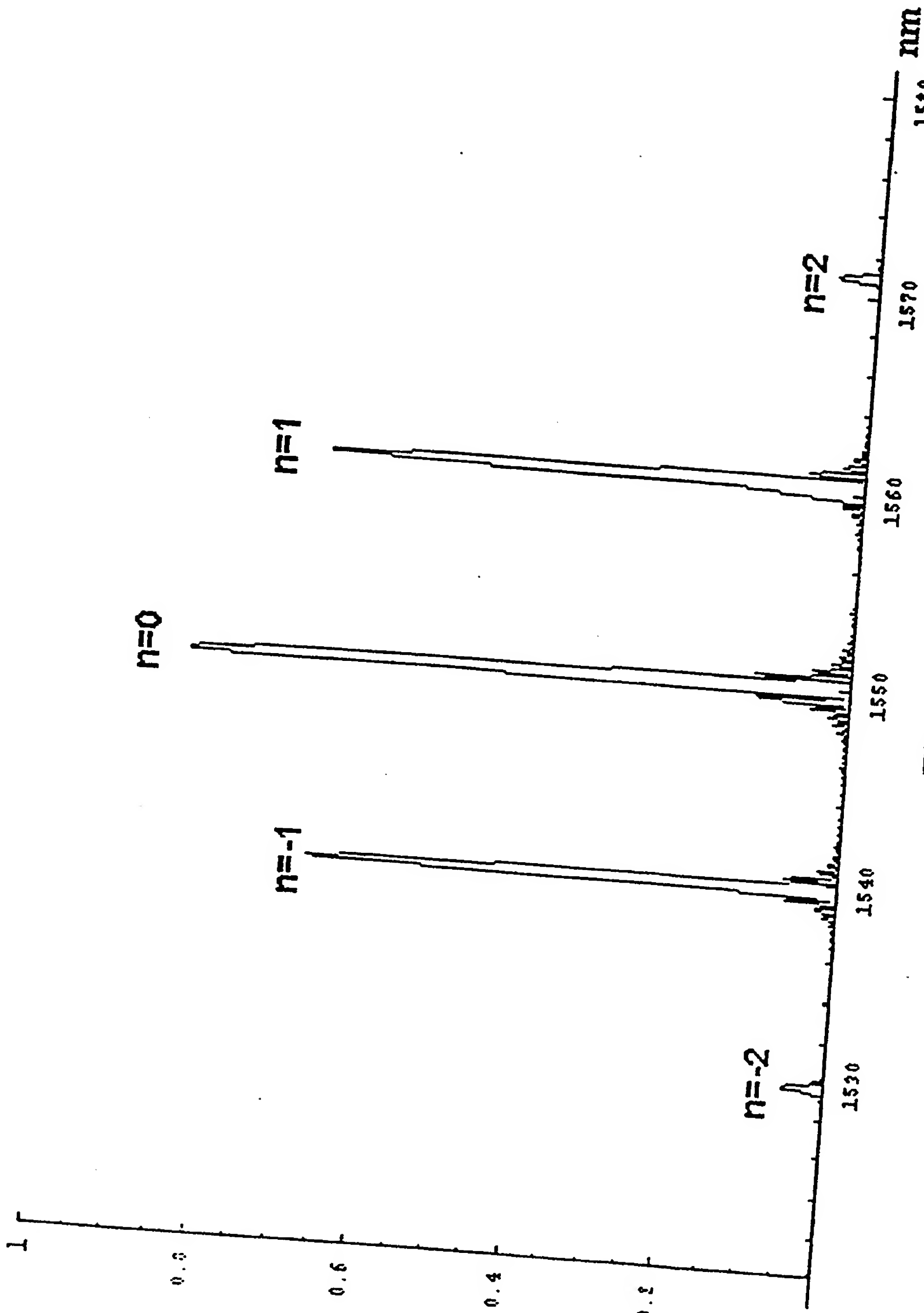

Fig. 3

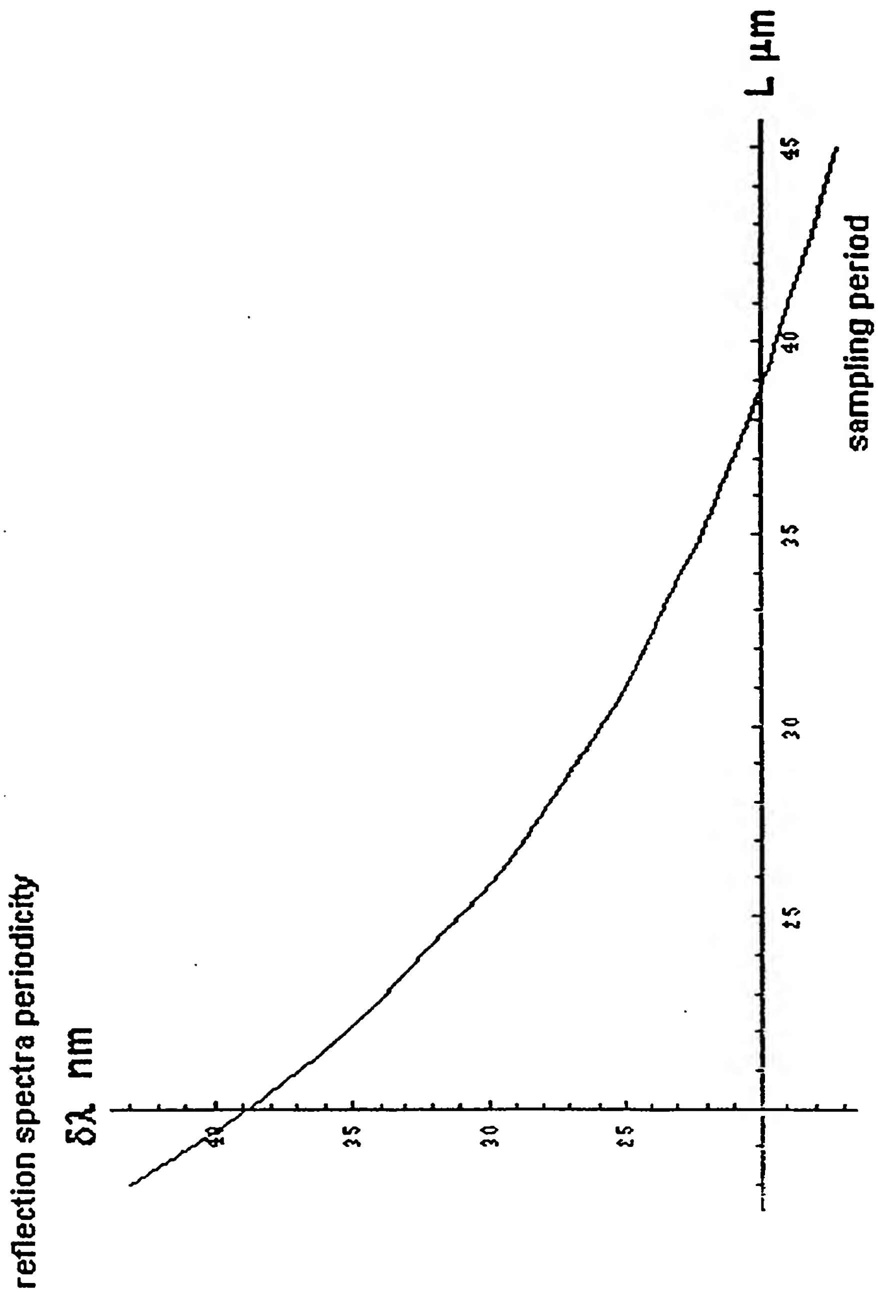
reflection spectra periodicity
δλ nm
40
35
30
25
L μm
25
30
35
40
45
sampling period

Fig. 4

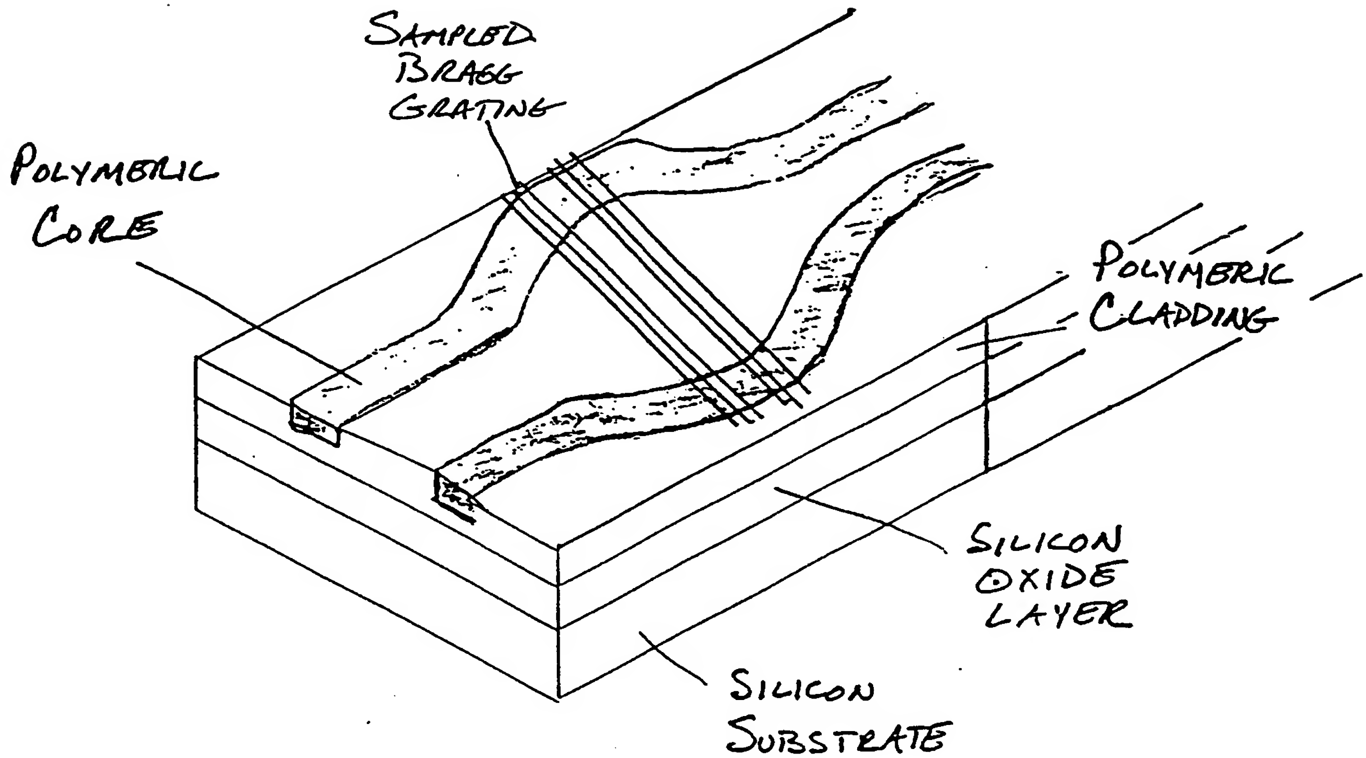
SAMPLED
BRAGG
GRATING
POLYMERIC
CORE
POLYMERIC
CLADDING
SILICON
OXIDE
LAYER
SILICON
SUBSTRATE

FIG. 5

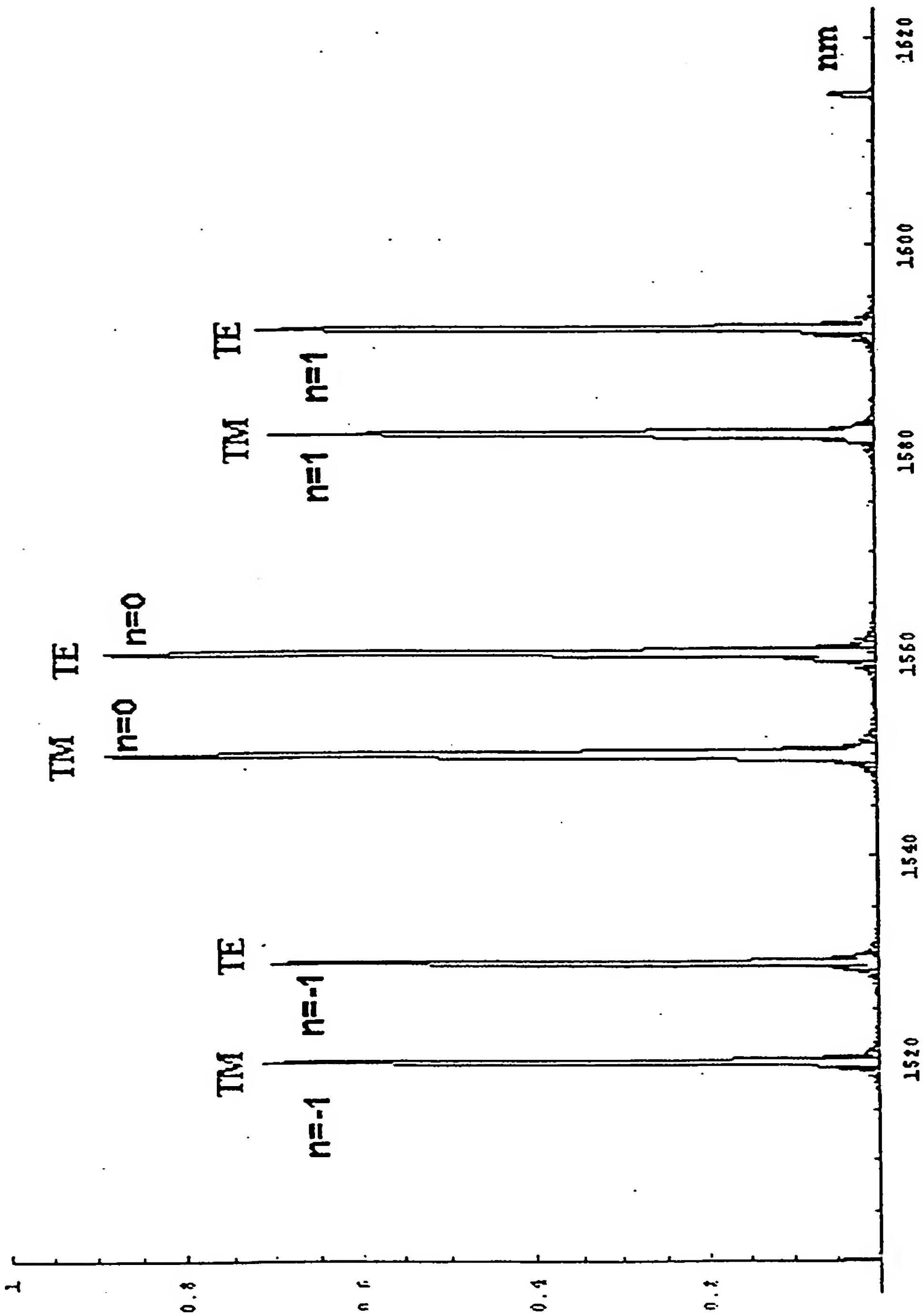
TM
TE
n=-1
n=-1
TM
TE
n=0
n=0
TM
TE
n=1
n=1
nm
1520
1540
1560
1580
1600
1620
1
0.8
0.4
0.2

Fig. 6

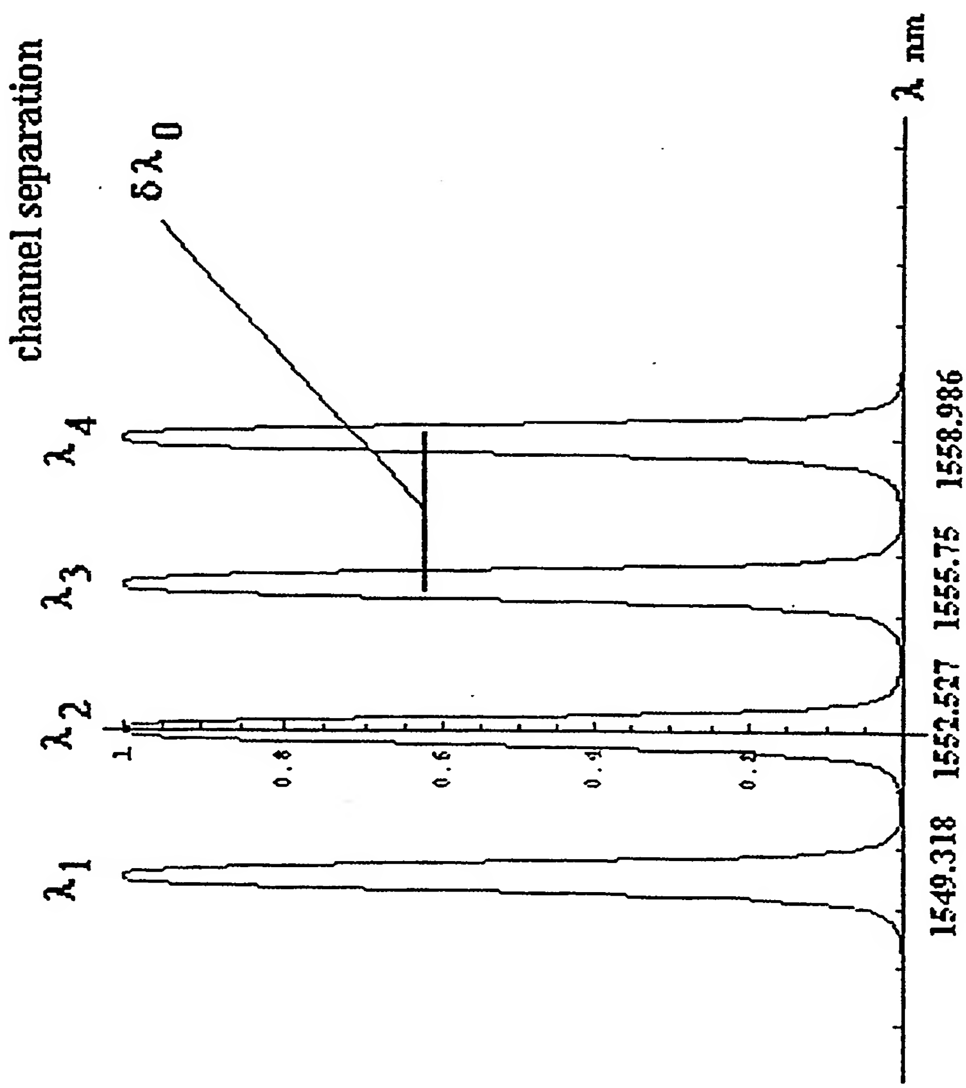
channel separation
$\delta\lambda_0$
λ nm
λ_1
λ_2
λ_3
λ_4
1
0.8
0.6
0.4
0.2
1549.318
1552.527
1555.75
1558.986

Fig. 7

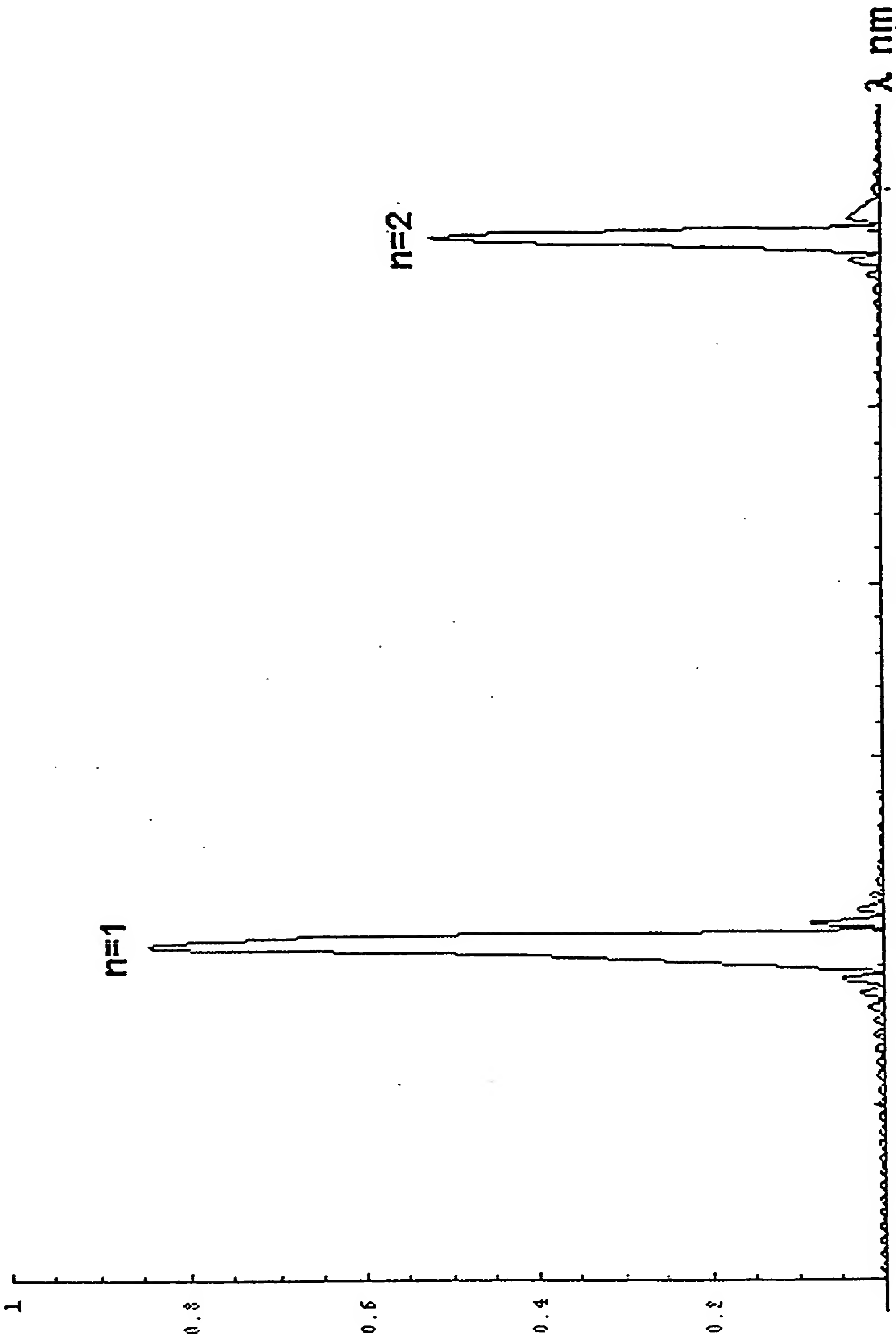

Fig. 9

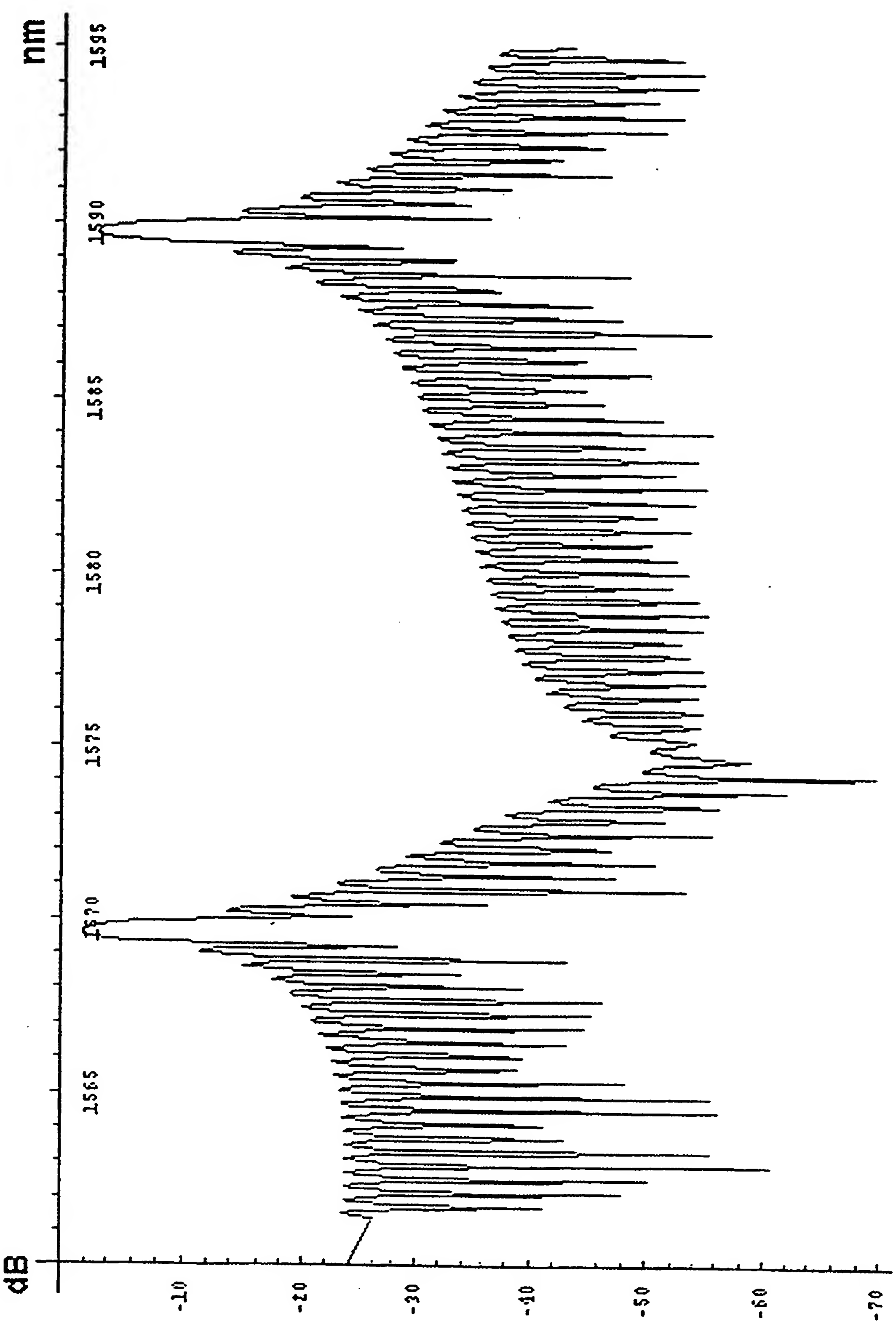

Fig. 10

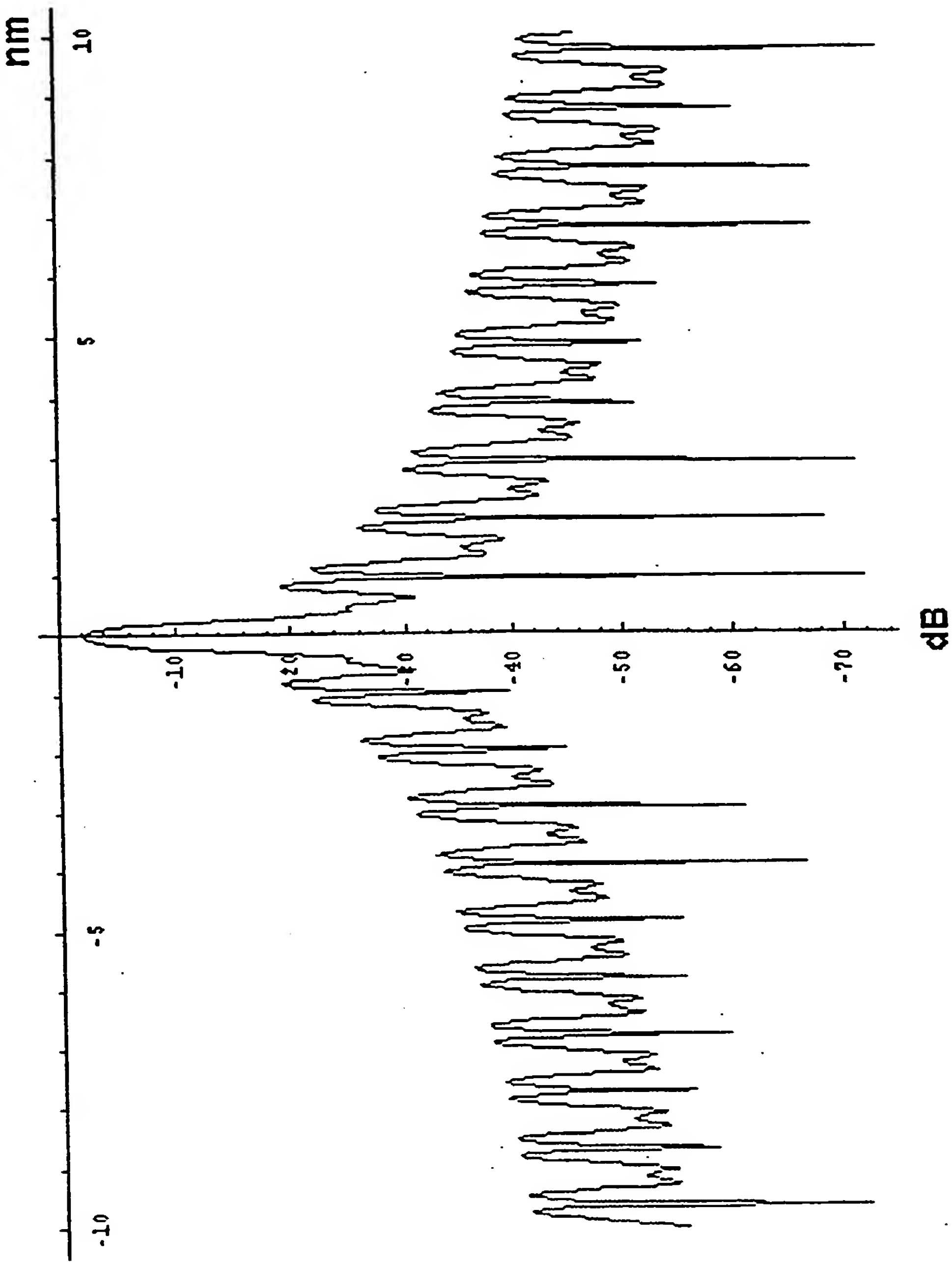

Fig. 12

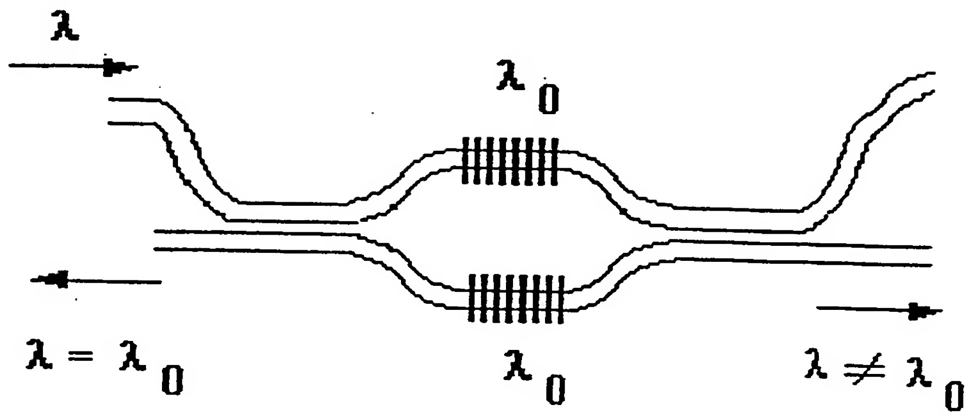
λ
λ_0
$\lambda = \lambda_0$
λ_0
$\lambda \neq \lambda_0$

Fig. 13

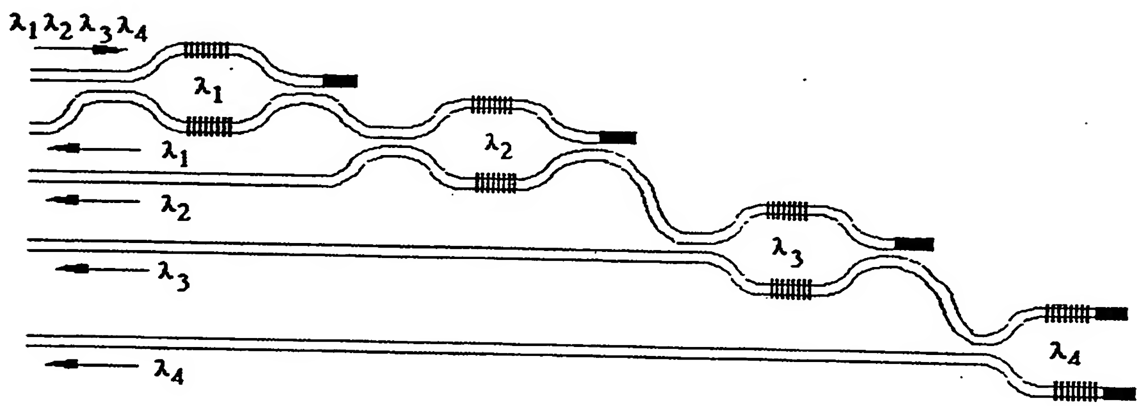
$\lambda_1 \lambda_2 \lambda_3 \lambda_4$
λ_1
λ_1
λ_2
λ_2
λ_3
λ_3
λ_4
λ_4

Fig. 14

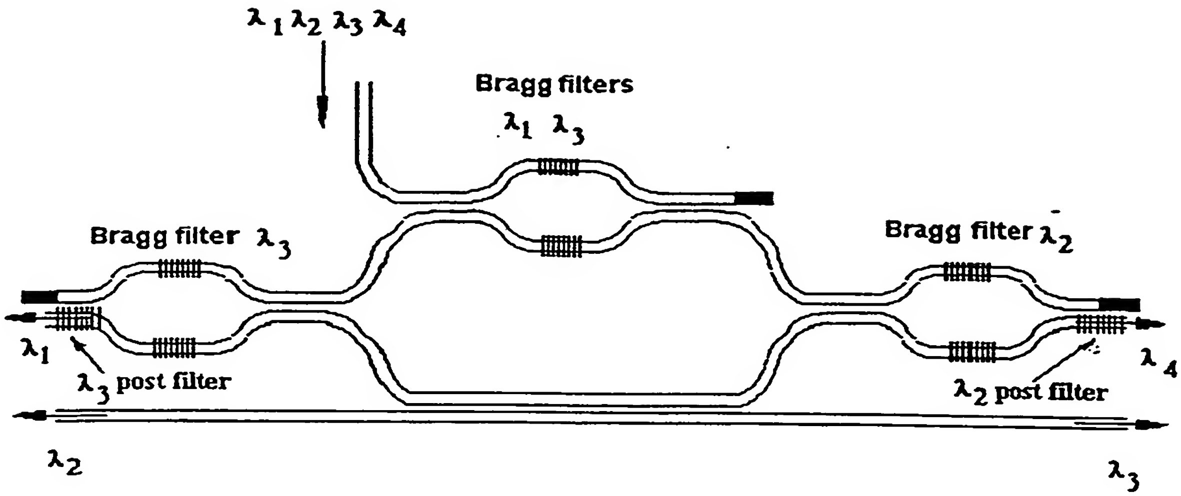
$\lambda_1 \lambda_2 \lambda_3 \lambda_4$
Bragg filters
λ_1 λ_3
Bragg filter λ_3
Bragg filter λ_2
λ_1
λ_3 post filter
λ_4
λ_2 post filter
λ_2
λ_3

Fig. 15

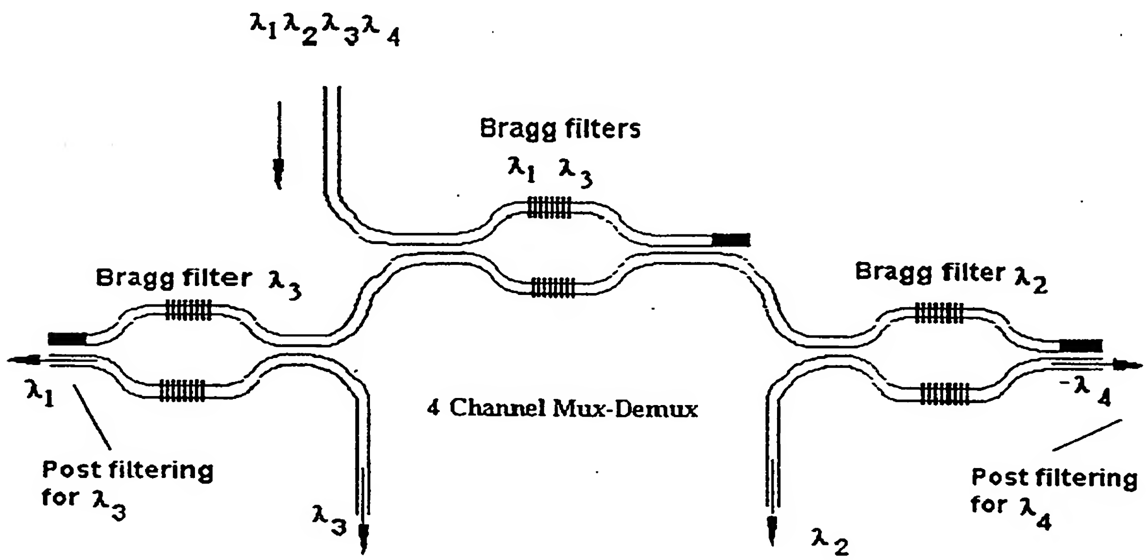
$\lambda_1 \lambda_2 \lambda_3 \lambda_4$
Bragg filters
λ_1 λ_3
Bragg filter λ_3
Bragg filter λ_2
λ_1
4 Channel Mux-Demux
λ_4
Post filtering for λ_3
λ_3
λ_2
Post filtering for λ_4

Fig. 16

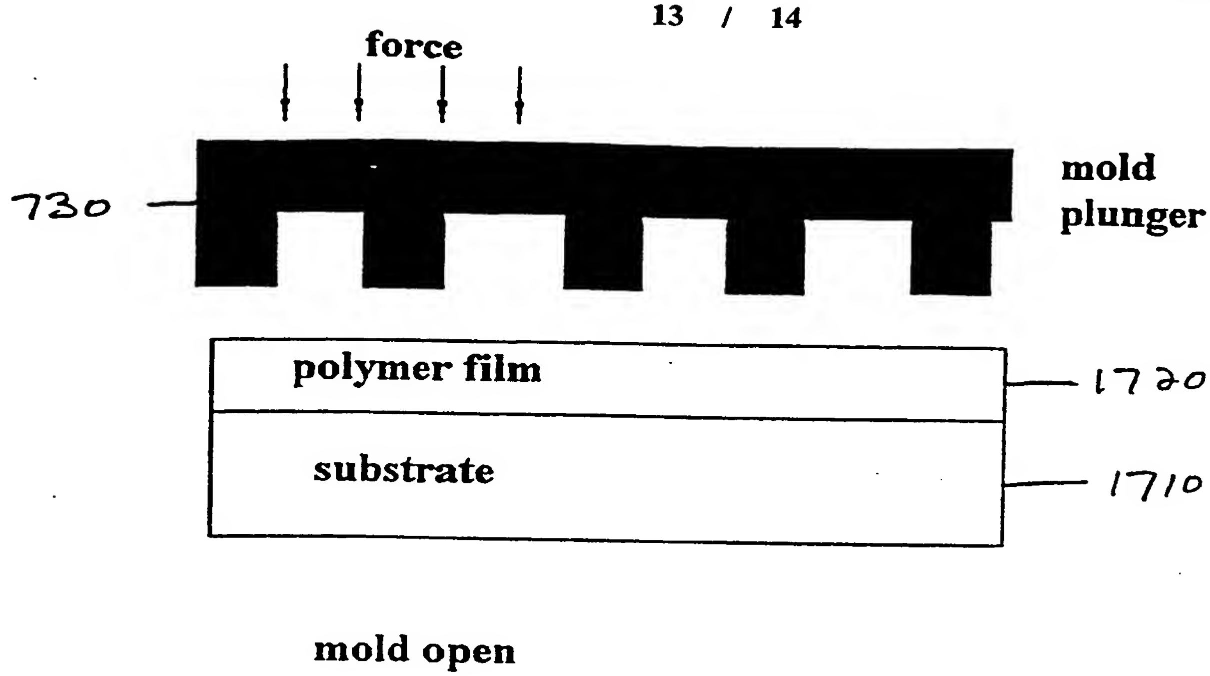
force
mold plunger
730
polymer film
1720
substrate
1710
mold open

FIG. 17

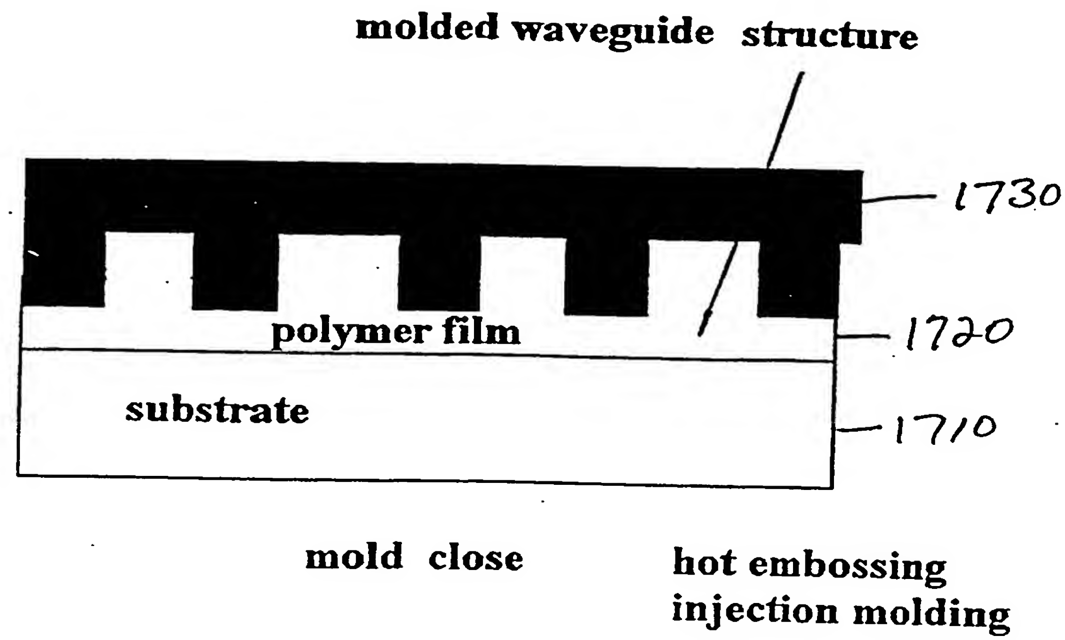
molded waveguide structure
1730
polymer film
1720
substrate
1710
mold close
hot embossing
injection molding

FIG. 18

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/03981

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02F1/225 G02B6/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G02B G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 791 842 A (LUCENT TECHNOLOGIES INC) 27 August 1997 see column 2, line 34 - column 4, line 50 see column 6, line 39 - column 7, line 33; figures 1,4,5 ---	1,6,9, 10, 21-23,37
Y	IBSEN M ET AL: "30DB SAMPLED GRATINGS IN GERMANOSILICATE PLANAR WAVEGUIDES" ELECTRONICS LETTERS, vol. 32, no. 24, 21 November 1996, pages 2233-2235, XP000683718 * see whole document * --- -/--	1,6,9, 10, 21-23,37

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 July 1999	21/07/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Wahl, M

2

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/03981

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
Y	JOUANNO J -M ET AL: "LOW CROSSTALK PLANAR OPTICAL ADD-DROP MULTIPLEXER FABRICATED WITH UV-INDUCED BRAGG GRATINGS" ELECTRONICS LETTERS, vol. 33, no. 25, 4 December 1997, page 2120/2121 XP000773570 see page 2120, left-hand column, paragraph 1 - right-hand column, paragraph 3; figures 1,2	1,6,9, 10,23
Y	EP 0 779 721 A (NORTHERN TELECOM LTD) 18 June 1997 see column 1, line 1 - column 3, line 22; figure 1	1,6,9, 10,23
A,P	EP 0 903 616 A (LUCENT TECHNOLOGIES INC) 24 March 1999 see page 1, paragraph 0002 - page 4, paragraph 0016 see page 6, paragraph 0025 - page 7, paragraph 0026; figure 1	12,13
A	WO 91 03748 A (HOECHST CELANESE CORP) 21 March 1991 * see whole document *	17,24-36

2

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 99/03981

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0791842 A	27-08-1997	US 5636309 A	03-06-1997
		AU 1475697 A	28-08-1997
EP 0779721 A	18-06-1997	GB 2308252 A	18-06-1997
		JP 9186674 A	15-07-1997
		US 5786914 A	28-07-1998
EP 0903616 A	24-03-1999	NONE	
WO 9103748 A	21-03-1991	GB 2236402 A	03-04-1991

Form PCT/ISA/210 (patent family annex) (July 1992)